Charles University in Prague

Faculty of Science

Study programme:
Anhropology and Human Genetics

Aix-Marseille University

ED 355, Espaces, Cultures, Societes

Study programme:
Prehistory

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BIOARCHAEOLOGY OF THE MEDIEVAL POPULATION OF CENTRAL EUROPE: RELATIONSHIPS AMONG HEALTH STATUS, SOCIAL CONTEXT AND NUTRITION

Bioarcheologie středověké populace střední Evropy: vztah zdravotního stavu, sociální diferenciace a výživy

Bioacheologie de population médievales en Europe centrale: Relations entre l´état sanitaire, la différentiation sociale et la nutrition

DISSERTATION

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Prague, 2016

DECLARATION

Hereby I declare that I worked out this thesis independently, using only the listed resources and literature, and I did not present it to obtain another academic degree.

Prague, 2016, September 20

Signature:

ACKNOWLEDGEMENTS

This dissertation would not have been possible without the support of many individuals and institutions. First of all, I wish to thank my supervisors, Petr Velemínský and Estelle Herrscher, whose theoretical, practical as well as moral help was essential toward completing this research. Also many thanks are due to Jaroslav Brůžek for a number of invaluable pieces of advice and comments and all sorts of encouragements, as well as for giving me the original idea to apply for the co-tutelle position. I thank the members of French Government Grant Committee for their belief in this project and to employees of the French Embassy in Prague for their help during preparation for my stays in France. I am also grateful to all members of LAMPEA for the hospitable welcome in the lab and especially to André Guy for his patience during my lab-work training.

This research would never have been possible without the help of Lumír Poláček, Jiří Macháček and Vladimír Sládek, who kindly extended access to some of the skeletal collections, including animal bones, and provided the archaeological background for the data interpretation.

I also thank all my colleagues from the Department of Anthropology in the National Museum in Prague for creating such a friendly and enthusiastic work environment. I am happy to have been part of this team.

I thank the funding sources that supported this research. These include the Ministry of Culture of the Czech Republic (DKRVO 2013/18 and DKRVO 2014/18, National Museum, 00023272) and the Grant Agency of the Charles University in Prague (project GA UK No.642413). The French government provided the grant covering the scholarship during my stays in France.

Finally, I thank my friends, family and namely František, for their continued support, patience and love during the long and often painful process of writing the thesis. Special thanks are due to one of my friends, whose encouragement helped me to get over the most troublesome page 61.

TABLE OF CONTENTS

DECLARATION iii

ACKNOWLEDGEMENTS iv

TABLE OF CONTENTS 1

ABSTRACT 6

ABSTRAKT 8

RÉSUMÉ 10

1 INTRODUCTION 12

1.1 Background and purposes of the study 12

1.2 Study Sample 13

1.3 Deriving the Hypotheses 14

1.4 Organization of Dissertation 17

2 BIOCULTURAL CONTEXT 19

2.1 Historical overview 19

2.2 The socio-economic and political structure of Great Moravia 21

2.3 Christianization 21

2.4 Urbanization 22

2.5 Natural conditions 23

2.6 Archaeological perspectives on Great Moravian diet 24

3 STABLE ISOTOPE ANALYSIS IN BIOARCHAEOLOGY 28

3.1 Nitrogen stable isotopes 29

3.2 Carbon 30

3.3 Non-dietary sources of carbon and nitrogen isotopic variability 31

3.3.1 Climate 31

3.3.2 Canopy effect 32

3.3.3 Fossil fuel emission 32

3.3.4 Husbandry and agricultural practices 33

3.3.5 Physiology – nitrogen balance 34

3.4 Collagen *vs.* carbonate 36

3.5 Sulphur 37

3.6 Isotopic analysis of breastfeeding 38

3.7 Sample diagenesis and contamination 40

4 SKELETAL INDICATORS OF HEALTH AND THEIR RELATION TO DIET 44

4.1 Relationship between diet and health 44

4.2 Breast-feeding, weaning and health 45

4.3 Studied health indicators 46

4.3.1 Dental caries 46

4.3.2 Periapical lesions 47

4.3.3 Periodontal disease (Periodontitis) 48

4.3.4 Dental wear 48

4.3.5 *Cribra orbitalia* and porotic hypersostosis 49

4.3.6 Endocranial lesions 50

4.3.7 Growth and stature 50

5 MATERIAL 52

5.1 The Great Moravian centers (GMC) 53

5.1.1 Mikulčice 53

5.1.1.1 Isotopic analysis of diet in Mikulčice 55

5.1.2 Pohansko 56

5.2 The Great Moravian hinterland (GMH) 58

5.2.1 Josefov I and Mutěnice 59

5.2.2 Prušánky I 60

5.3 The late Hillfort sample 61

5.3.1 Louky od Břeclavska and Kostice 61

5.3.2 Josefov II ... 63

6 METHODS ... 64

6.1 Sex and age estimation ... 64

6.2 Sampling strategy and sample treatment for isotopic analysis ... 65

6.3 Collagen extraction method ... 65

6.3.1 Demineralization ... 66

6.3.2 Purification (Removal of organic contaminants) ... 66

6.3.3 Solubilization of collagen particles ... 66

6.3.4 Freeze-drying and final sample treatment ... 66

6.3.5 Stable isotope ratio analysis ... 67

6.4 Apatite preparation method ... 67

6.5 Osteological analysis ... 67

6.6 Statistical analysis ... 69

7 RESULTS AND DISCUSSION ... 71

7.1 Isotopic data of fauna ... 71

7.1.1 Data quality ... 71

7.1.2 Animal data as a proxy for the isotopic characteristic of environment and human-environmental interaction ... 73

7.1.3 Stable isotope analysis of sulphur in animal samples ... 82

7.2 Isotopic data of adults ... 85

7.2.1 General overview of the Great Moravian diet ... 85

7.2.2 Mikulčice ... 88

7.2.3 Pohansko ... 93

7.2.4 Josefov I ... 99

7.2.5 Late Hillfort sites (Louky od Břeclavska and Josefov II) ... 104

7.2.6 Comparison between sites (intra-population variability and diachronic trends in diet) 109

7.2.6.1 Diet in Great Moravian centers ... 110

7.2.6.2 Great Moravian centers *vs.* hinterland (urban-rural differences.) 114

7.2.6.3 Late Hillfort sample and the diachronic trends in diet 116

7.2.7 Apatite results 118

7.3 Isotopic data of sub-adults 123

7.3.1 Mikulčice 123

7.3.1.1 Sample preservation 123

7.3.1.2 Weaning pattern in Mikulčice sample (nitrogen isotopic data) .. 125

7.3.2 Josefov 126

7.3.2.1 Sample preservation 126

7.3.2.2 Weaning pattern in Josefov sample (nitrogen isotopic data) 128

7.3.3 Intra-population variability in feeding practices 129

7.3.4 Stable carbon isotopes 132

7.3.5 Methodological concerns 135

7.3.6 The comparison of cross-sectional *vs.* intra-individual sampling strategy .. 137

7.4 Relationship anmong health and dietary indicators 141

7.4.1 Diet and health in adult sample 141

7.4.2 Weaning strategies in relation to health 152

8 CONCLUSION: DIET AND HEALTH PATTENS IN MEDIEVAL MORAVIA 160

9 SOUHRN (CZECH SUMMARY) 163

9.1 Úvod 163

9.2 Cíle práce 165

9.3 Materiál a metody 167

9.4 Izotopová data: výsledky a diskuze 169

9.4.1 Izotopové hodnoty souboru zvířat 169

9.4.2 Lidské izotopové hodnoty souboru dospělých 171

9.4.3 Lidské izotopové hodnoty souboru nedospělých 173

9.5 Vztah výživy a ukazatelů zdravotního stavu ve velkomoravské populaci ... 175

9.6 Hlavní závěry ... 177

10 RÉSUMÉ (FRENCH SUMMARY) ... 179

10.1 Introduction ... 179

10.2 Objectifs de l'étude ... 182

10.3 Matériel et méthodes ... 184

10.4 Résultats et discussions ... 186

10.4.1 Les valeurs isotopiques du groupe d'animaux ... 186

10.4.2 Les valeurs isotopiques humaines des adultes ... 187

10.4.3 Les valeurs isotopiques des sujets immatures ... 191

10.5 La relation entre l'alimentation et les indicateurs de l'état de santé de la population de la Grande-Moravie ... 193

10.6 Conclusions principales ... 195

REFERENCES ... 197

LIST OF ABBREVIATIONS ... 231

LIST OF TABLES ... 232

LIST OF FIGURES ... 235

LIST OF EQUATIONS ... 239

APPENDIX: DATASETS (COMPLETE ISOTOPIC DATA) ... 240

ABSTRACT

We studied the dietary behavior and health status of a population that lived in the context of rapid change, including the development of the economic and political structures of states, the adoption of Christianity as well as the subsequent disruption of social structure and the recovery of society.

Carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic values were measured in a sample of 189 adult individuals of both sexes and 74 animals representing different socio-economic contexts (power centers versus the hinterlands) and chronology: the Great Moravian (9th - 10th century AD) versus late Hillfort (11th century AD) period. A sample of 41 sub-adults aged 0–6 years, representative of both Great Moravian power centers (Mikulčice) and its rural hinterlands (Josefov), was selected for isotopic analyses of breastfeeding and weaning behavior.

Data on growth and frequency of nonspecific stress indicators (*cribra orbitalia,* porotic hyperostosis, and endocranial lesions) were analyzed in a sub-adult group. In adults, we focused on dental health (caries, periapical lesions, dental wear, and periodontal disease), the presence of *cribra orbitalia* and estimated adult stature.

Isotopic data of the adult sample showed that the Great Moravian population had a terrestrial diet with a substantial proportion of C_4 plants. Our data does not reflect significant consumption of freshwater fish. Dietary analysis revealed statistically significant differences in the consumption of animal protein between power centers and the hinterlands. In power centers, significant relationships were found between nitrogen isotopic values and indicators of socio-economic status in males but not in females. Diachronic changes in the diet were observed: the diet of the 11th century sample was characterized by higher consumption of C_4 plants (millet) in both sexes and lower consumption of animal protein in males.

For sub-adults, the isotopic results suggested there was not solely one established norm for the duration of breastfeeding in the Great Moravian population. In the sample from the power center in Mikulčice, some children may have been weaned during their second year, while others may have still been consuming breast milk substantially up to four to five years of age. By contrast, data from the hinterland sample in Josefov showed more homogeneity, with a gradual cessation of breastfeeding starting after the age of two.

These results confirmed that Great Moravia represented a highly stratified society socio-economically. Social status appears to have determined the consumption of animal protein much more in males than in females. The diet of females also proved to be more uniform in the diachronic frame. The diachronic change in dietary behavior suggested that even after the apparent recovery in the 11th century, Moravian society did not reach its original level of welfare at least in terms of the quality of diet.

The quality of diet significantly influenced dental health in the Great Moravian population sample. The observed relationship between nitrogen isotopic values versus dental caries and periodontitis agreed well with the generally shared opinion that a diet low in animal protein and rich in carbohydrates promoted both cariogenesis and periodontitis.

In contrast, there is no evidence that observed weaning strategies affected the level of biological stress, which the sub-adult population of the Great Moravian power center had to face compared to those in the hinterland.

Key words: diet, stable isotopes, breastfeeding, health status, Middle Ages, Great Moravia, socio-economic stratification

ABSTRAKT

Práce se zabývá výživou a zdravotním stavem středověké populace Moravy (9. – 11. století) v kontextu společenských změn, zahrnujících rozvoj ekonomických a politických struktur, přijetí a rozvoj křesťanství, ale i následný úpadek státní struktury a opětovný populační rozvoj v průběhu mladohradištního období.

Výživa byla hodnocena na základě stabilních izotopů uhlíku ($\delta^{13}C$) a dusíku ($\delta^{15}N$). Hodnoty izotopů $\delta^{13}C$ a $\delta^{15}N$ byly měřeny u souboru 189 dospělých jedinců obou pohlaví a 74 zvířat. V hodnoceném souboru byly zastoupeny dvě socio-ekonomicky odlišné populační skupiny (mocenská centra *vs.* jejich zázemí) a dvě časová období: velkomoravské období (9. – 10. století) a období mladohradištní (11. století). Hodnoty izotopů $\delta^{13}C$ a $\delta^{15}N$ byly měřeny i u dětí ve věku do šesti let z mikučické akropole a jejího zázemí (Josefov) z důvodu studia délky kojení a věku odstavení dítěte.

U nedospělých jedinců byla sledována přítomnost vybraných nespecifických stresových indikátorů (*cribra orbitalia*, porotická hyperostóza, endokraniální léze) a odečtena metrická data definující růst. U dospělých jedinců byl hodnocen zdravotní stav chrupu (přítomnost zubního kazu, periodontitidy, periapikálních lézí, intenzita zubní abraze), přítomnost *cribra orbitalia* a odhadnuta výška postavy.

Hodnoty $\delta^{13}C$ a $\delta^{15}N$ souboru dospělých ukazují, že strava velkomoravské populace byla založena na suchozemských zdrojích s významným podílem C_4 rostlin. Významná konzumace sladkovodních ryb nebyla prokázána. Byly pozorovány významné rozdíly v podílu živočišných proteinů ve stravě mezi obyvateli center a jejich zázemí. V rámci populace center byl v souboru mužů nalezen statisticky signifikantní vztah mezi hodnotami stabilních izotopů dusíku a indikátory socio-ekonomického postavení jedince. U žen analogický vztah nalezen nebyl. Dále byly pozorovány diachronní změny ve výživě, kdy strava mladohradištního souboru byla charakterizována zvýšenou konzumací prosa u obou pohlaví a nižším zastoupením živočišných proteinů ve stravě mužů.

Izotopová data souboru nedospělých ukazují, že pro velkomoravskou populaci neexistovala jediná závazná norma pro délku kojení. V souboru z Mikulčic byla patrná vysoká variabilita délky kojení, kdy některé z dětí byly odstaveny v průběhu druhého roku života, zatímco jiné konzumovaly významné množství mateřského mléka ještě ve věku 4-5 let. Data souboru z Josefova oproti tomu vykazovala vyšší homogenitu, kdy proces odstavení byl zahájen po druhém roce věku.

Výsledky této studie ukazují, že Velkomoravská společnost vykazovala relativně vysokou míru socio-ekonomické stratifikace. Sociální postavení mělo pravděpodobně vyšší vliv na stravu mužů než žen. Strava žen se také ukazuje být stabilnější napříč časovými obdobími. Pozorované diachronní změny ve výživě naznačují, že i přes zjevný opětovný populační rozvoj v 11. století, kvalita životních podmínek (alespoň pokud jde o kvalitu výživy) zaostávala za obdobím velkomoravským.

Byl prokázán statisticky signifikantní vliv kvality stravy na stav chrupu velkomoravské populace. Pozorovaný vztah mezi hodnotami stabiliních izotopů dusíku, kazivostí chrupu a výskytem periodontitidy je v souladu s obecně platnou premisou, že strava chudá na živočišné proteiny s vysokým podílem sacharidů zvyšuje riziko výskytu zubního kazu a periodontitidy.

Nebylo prokázáno, že by pozorované strategie odstavení ovlivnily riziko biologického stresu, kterému čelily populační skupiny mikulčického centra, respektive jeho zázemí.

Klíčová slova: výživa, stabilní izotopy, kojení, zdravotní stav, středověk, Velká Morava, socio-ekonomická stratifikace

RÉSUMÉ

Le présent travail se concentre sur l'alimentation et l'état de santé de la population dans le contexte des changements sociaux rapides, y compris le développement des structures économiques et politiques, l'adoption du christianisme, son déclin postérieur et la restauration des structures étatiques.

Le travail s'est concentré sur la mesure des valeurs des isotopes stables du carbone ($\delta^{13}C$) et de l'azote ($\delta^{15}N$) dans un groupe de 189 adultes des deux sexes et 74 animaux. Le groupe étudié était représenté par différents ensembles de populations (les centres du pouvoir *vs.* l'arrière-pays) et périodes : la Grande-Moravie (IX^{e} – X^{e} siècles) et la période de « late Hillfort » (XI^{e} siècle). L'analyse a également concerné un groupe d'immatures âgés de moins de six ans, comprenant des individus des centres de la Grande-Moravie et de l'arrière-pays, en vue de l'analyse isotopique de l'allaitement maternel et du sevrage.

Le groupe des immatures a fait l'objet d'une analyse de la présence des indicateurs de stress non spécifiques (*cribra orbitalia*, hyperostose porotique, lésions intracrâniennes) et des données métriques définissant la croissance. Chez la population adulte, le travail s'est concentré sur l'état de la dentition (présence de caries, parodontite, lésions périapicales, intensité de l'abrasion dentaire), la présence de *cribra orbitalia* et l'évaluation de la stature.

Les données isotopiques du groupe des adultes indiquent que l'alimentation de la population de la Grande-Moravie était basée sur les ressources terrestres riches en plantes dites en C_4. La consommation significative des poissons d'eau douce n'a pas été prouvée. Des différences dans la proportion des protéines animales ont été observées au niveau de l'alimentation des habitants des centres et de leur arrière-pays. Une relation significative entre la proportion des protéines animales dans l'alimentation et le statut socio-économique de l'individu a été statistiquement observée dans le groupe des hommes de la population des centres. Une relation similaire n'a pas été découverte chez les femmes. Des modifications diachroniques ont été observées au niveau de l'alimentation – l'alimentation du groupe de la période de late Hillfort était caractérisée par une consommation significative de plantes en C_4 (millet) chez les deux sexes et la contribution moindre des protéines animales au niveau de l'alimentation des hommes.

Les données isotopiques du groupe des immatures indiquent que la population de la Grande-Moravie ne connaissait aucune norme obligatoire pour la durée de l'allaitement maternel. Le groupe de Mikulčice enregistre une forte variabilité de la durée de l'allaitement maternel : certains nourrissons étaient sevrés dans le courant de la deuxième année de leur vie, alors que d'autres nourrissons continuaient de consommer d'importantes quantités de lait maternel à l'âge de 4-5 ans. Par contre, les données du groupe de Josefov montrent une homogénéité des pratiques caractérisée par un sevrage de la majorité des nourrissons après la deuxième année de leur vie.

Les résultats de cette étude démontrent que la société de la Grande-Moravie présentait un taux élevé de stratification socio-économique. Le statut social a probablement eu une plus grande influence sur le régime alimentaire des hommes que sur celui des femmes. Le régime alimentaire des femmes apparait plus stable au cours des différentes périodes. Les changements diachroniques observés au niveau de l'alimentation indiquent que malgré le développement apparent de la population au XI^{e} siècle, la qualité des conditions de vie (au moins en termes d'alimentation) accuse une aggravation par rapport à la période de la Grande-Moravie.

Les statistiques ont démontré l'impact significatif de la qualité de l'alimentation sur l'état de la dentition de la population de la Grande-Moravie. La relation observée entre les valeurs des isotopes stables de l'azote et l'occurrence des caries dentaires et de la parodontite est conforme au principe généralement accepté selon lequel une alimentation pauvre en protéines animales et riches en glucides augmente le risque de caries dentaires et de parodontite.

Il n'a pas été démontré que les stratégies de sevrage observées ont influencé le risque de stress biologique auquel ont dû faire face les groupes de population des centres et de l'arrière-pays.

Mots-clés : alimentation, isotopes stables, allaitement maternel, état sanitaire, Moyen Âge, Grande-Moravie, stratification socio-économique

1 INTRODUCTION

1.1 Background and purposes of the study

In the area of what is today called Central Europe, the final phase of the early Middle Ages and the onset of the High Middle Ages (ca. AD 700 – 1100) were a period of dramatic socioeconomic, political and religious transformations, leading from egalitarian communities to the stratified societies of the first Christian states that formed the origins of Europe's present form (Berend et al. 2013). The impact of these unprecedented changes on every-day life style and general well-being of populations has been the subject of intensive interest for several generations of researchers in the field of archeology and bioarchaeology (e.g. Bigoni et al. 2013; Dostál 1990; Havelková et al. 2010; Kaupová et al. 2014; Macháček 2013a; Poláček and Marek 1995; Poulík 1970; Sládek et al. 2015; Stloukal 1970; Stloukal and Vyhnánek 1976; Velemínský and Poláček 2008).

Human skeletal remains provide the primary biological evidence about the different aspect of life of past populations such as health status and physical well-being, developmental stress, manipulative behavior and work-load etc. (Larsen 1997; Lewis 2007). But concerning human diet, the traditional anthropological evaluation of human skeletons provided only indirect information on this bio-socio-cultural phenomenon and crucial determinant of health and physical well-being. So for a long time, dietary reconstruction of past populations relied mainly on archaeozoology and archaeobotany. These undoubtedly greatly supplement the records of diet but still only provide bulk data without informing us how foods were distributed within the population. From the medieval period onwards, historical records may extend our knowledge of past dietary behavior (Beranová 2005) but, especially for the early medieval period, these are still scarce. Moreover, they most commonly focus on elite classes while the daily lives of individuals from lower ranks of society are under-represented (Müldner and Richards 2005).

In contrast, stable isotope analysis of bone and teeth produces clear and direct results concerning the diet of particular individuals, enabling a nuanced interpretation of diet where evidence such as differential access to foods across sex, age and status groups can be considered. By this way we obtain information about the proportions of animal protein, fish and C_4 plants at an individual level (Katzenberg 2007; Lee-Thorp 2008; Schwarcz and Schoeninger 2012).

Recently stable isotopes have been used to identify variable dietary patterns in medieval Europe (Hakenbeck et al. 2010; Kjellström et al. 2009; Müldner et al. 2009;

Müldner and Richards 2005; Polet and Katzenberg 2003; Reitsema 2012b; Reitsema et al. 2010; Reitsema and Vercellotti 2012; Schutkowski et al. 1999).

The relationship between diet, as identified by stable isotopes, and socio-economic status of a particular individual, as defined by location of the grave, type of burial and/or the grave goods, has been confirmed in numerous medieval European populations (Czermak et al. 2006; Kjellström et al. 2009; Reitsema and Vercellotti 2012; Yoder 2012). A more general view of some of these results suggests that socio-economic differences in diet had been increasing in importance in the course of the Middle Ages (Hakenbeck 2013). Similarly, the reflection of cultural (especially religious) beliefs influencing diet could be seen in isotopic dietary records (Barrett and Richards 2004; Rutgers et al. 2009; Salamon et al. 2008).

My purpose here is to reconstruct diet in medieval Moravia and explore its variation within a population, using stable carbon and nitrogen signatures in human bone (and teeth) recovered from a period of extreme sociopolitical and economic change.

1.2 Study Sample

Five skeletal samples investigated in this study come from the same geographic region of South Moravia, i.e., the true core of the Great Moravian Empire. They could be divided according to two basic criteria: In the diachronic perspective, we focused on the Great Moravian (9th – beginning of 10th century AD) and late Hillfort (11th century) periods. Regarding the socio-economic context, they are representative of the power centers and their (mainly agricultural) hinterland. However, this strict division could be applied only on the Great Moravian samples. In the late Hillfort period, when the social structure became more complex (Lozny 2004), this simplification is no longer valid. Moreover, in cases when the corresponding settlement was not found or explored, a growing uniformity of burial rite (Unger 2006) makes it difficult to tease out the issue of socio-economical structure of the buried population (for more details, see the Chapter 5).

To reconstruct the local isotopic baseline, animal bones were analyzed - ideally coming from the same sites. In the case of the Great Moravian hinterland and late Hillfort samples, this was not possible because only graveyards – without corresponding settlement areas – were uncovered. In these cases, bones from the sites spatially close and of the same date were sampled, raising the final number of studied sites to seven.

Diets of the population groups defined above were reconstructed and interpreted and the rate of diet change examined.

1.3 Deriving the Hypotheses

Generally, this study addresses two of the important issues in anthropology: 1) the relative roles of biological (sex, age, health) and cultural (social status, religion) factors in structuring human diet, and 2) how human dietary behavior may respond to social, economic and political changes.

While in egalitarian societies, sex and age are important in defining social roles. Along with the growing social complexity, cultural factors such as religion and status become increasingly important for structuring social relationships (Reitsema 2012b). Development of social differences within human societies is thus reflected in diet quality and diversity. Diet, especially the proportion of animal protein, proved to be often linked to socio-economic status in medieval populations (Hakenbeck 2013; Kjellström et al. 2009; Yoder 2012). Increasing socio-economic differences in diet observed during the Middle Ages (Hakenbeck 2013) may be seen as a reflection of the above outlined phenomenon.

Accordingly, the character of diet may reflect the attained degree of social complexity of Great Moravia, as proposed by the following hypotheses.

H1: higher consumption of animal protein may be expected in inhabitants of Great Moravian centers when compared to the agricultural population of their hinterland. Due to the assumed higher social stratification, the diet in these centers should be more variable.

H2: The socio-economic status (as reflected in burial rite) should be also reflected by the different quality of diet.

By a number of bioarchaeological studies the adverse impact of the urbanization was observed across a wide range of human populations, demonstrating the declining health of people living in increasingly large, agglomerated settlements. Without doubt, limited access of members of the lower classes to varied foods was one of the detrimental agents acting in growing urban areas. The diet of the newly established group of the urban poor was characterized by increased homogeneity and a heavier reliance on cereal crops, which can both lead to malnutrition (Koepke and Baten 2005; 2008; Komlos 1998; Larsen 1997). If the urbanization process proceeded to a high enough degree in the case of Great Moravian centers, we may hypothesize the following:

H3: For the population of centers, the diet of the low-status group is the most homogenous and of worse quality than that of inhabitants of the hinterland.

Another force of human dietary change, which may have played an important role in the 9th century population, is Christianity. Religiously motivated fasting is often reflected in the isotopic signal of medieval populations due to the increased consumption of fish as the allowed fasting meal (Barrett and Richards 2004; Müldner et al. 2009; Rutgers et al. 2009). Although from historical sources we have some information on the fasting prescription imposed on recently Christianized populations of the 9th century (Bartoňková et al. 1971), an outstanding question, that these records do not resolve, is whether these fasts were observed by the general population or at least by some of its groups.

The process of Christianization is supposed to have advanced in the course of the 9th century but also, according to the socio-economic gradient, from centers and their elites to the lower classes and more distant settlements of the hinterland (Poláček 2008b). Accordingly:

H4: Different pressure to abide by Christian rules, including the fast prescriptions, could be expected. If this was the case, the inhabitants of centers and especially elite groups are supposed to have consumed a higher amount of fish. The consumption of fish in the population of centers may be also augmented by their location in the flood plains, offering perfect opportunities for fishing.

And finally, another objective of this study is to detect diachronic change of diet. Naturally, the best way to observe the impact of the above outlined unprecedented changes of society would be through comparison with the pre-Great Moravian population. This is however not possible due to the tradition of the cremation burial rite, which was widespread in this territory until the turn of the 8th and 9th centuries (Klanica 1990; Měřínský 2006). Thus we can only study potential changes in diet in relation to the fall of Great Moravia.

The decline of Great Moravia, together with the worsening climatic conditions, are supposed to have affected the diet in terms of both protein consumption and the spectrum of consumed crops. On the other hand during the late Hillfort period the population is supposed to have already adapted to different natural, as well as socio-economic, conditions (Macháček 2013b). The way these changes and subsequent adaptations are reflected in the diet of Moravians may be summarized as follows:

H5: During the final phase of the Great Moravian period, the worsening of the dietary status is supposed in the population of GM centers due to the impoverishment of the population and the disruption of the food distribution system.

H6: During the 11th century, the diet of the population is supposed to have been of better quality due to the adaptation to new climatic and societal conditions. The dismissing of close proto-urban centers would also have contributed to the better quality of diet because, without the necessity to supply the urban population of a center, more of the quality foodstuff could be kept in rural households (Koepke 2002; Komlos 1985; 1998).

Our understanding of how the above mentioned changes affected child care and how sub-adults responded to it is very limited. Concerning the sub-adult data set, this study is focused on the comparison of the infant feeding practices between the population of Great Moravian centers and their hinterlands. From all the above mentioned societal changes, only the effect of Christianization may be described with some certainty, based on the contemporary written sources transmitting the opinions of Church authorities concerning family and sexual life. Based on these resources (Bartoňková et al. 1971) one may hypothesize:

H7: Shortening of the period of breastfeeding in the urban population due to the more rapid introduction of Christian rules and taboos,

Consequently, potential differences in diet of both children and adults are supposed to be linked to differences in health and growth (and thus attained adult stature) in the sample of the Great Moravian population.

Due to the fact that until now, with one exception (Halffman and Velemínský 2015) very little has been done to define the isotopic background in the context of the Moravian (or Czech in general) Middle Ages, quite a thorough study of animal isotopic values is performed as a part of this study, focusing on the following issues:

H8: The presumably different environmental condition of the flood plain and hinterland may result in distinct isotopic values of animals grown in these contexts.

H9: Applied husbandry or land management practices may be reflected by isotopic differences between wild and domesticated animals.

H10: The change of environmental conditions as well as development in agricultural and husbandry practices will result in changes in isotopic background between the Great Moravian and late Hillfort period.

Concerning the animal data set, special attention will be paid to the isotopic values of pigs, which were documented to be another important indicator of the degree of urbanization. This is based on the premise that, along with the proceeding urbanization, a decline in consumption of meat from cattle and wild animals in favor of the meat from pigs and chickens occurred. These could be raised in limited spaces close to human households and so were used to solve the urban food problem. This was connected with the change of breeding practices, which is reflected in the isotopic values of pig bones (Hammond and O'Connor 2013). Traditional practice, where pigs were allowed to feed freely on local vegetation, results in isotopic values typical for the ecological niche of local herbivores. On the other hand, when kept in the midst of urban settlements and fed with scraps of human food, the isotopic values of pigs reflect the "household ecological niche" i.e., values similar to those of dogs or fowl (Knipper et al. 2013; Reitsema et al. 2013). So again, if the urbanization process proceeded to a sufficient degree in the case of Great Moravian centers, we may hypothesize:

H11: Isotopic values of domesticated pigs are out of the range for domesticated herbivores, reflecting an omnivorous diet similar to that of fowl.

More information on the environmental as well as anthropogenic sources of isotopic variability may be found in Chapter 3.

1.4 Organization of Dissertation

This dissertation is organized into 8 main chapters. In Chapter 2 I present the biocultural context of Great Moravia with some extent into late Hillfort period. This chapter provides the necessary background information for the questions addressed above and describes the political and socioeconomic as well as environmental context of Moravia in the early medieval and at the beginnings of the high medieval period. Also the evidence for diet and subsistence strategies provided by archaeozoology and palaeobotany is briefly summarized here. Chapter 3 introduces the basic principles of stable isotope analysis used for dietary reconstruction as well as the boundaries and limitations of this tool. Chapter 4 describes breifly the relation between diet and health status and introduces the skeletal indicators of health included in this study. Chapter 5 summarizes all the basic information on the skeletal material included into the study and provides archaeological background for all the studied sites. Chapter 6 deals with the methods of sample preparation and analysis used in the study. Chapter 7 presents the results of all stable isotope analyses as well as osteological examinations and is divided into four parts: (1) animal isotopic data, (2) isotopic data of adults (3) isotpic data of sub-adults and finally (4) discussion on the potential relationship between isotopic and osteological data. The discussion of the results in light of the biocultural context is also the part of this section. Finally Chapter 8 summarizes the main conclusions.

2 BIOCULTURAL CONTEXT

2.1 Historical overview

The era of the Great Moravian Empire (the 9th to beginning of the 10th century AD) is a crucial period in the history of Central Europe, where, on the boundary between the spheres of influence of Byzantium and the Frankish Empire, the basis of the first Slavic state formation occurred (Poláček 2008b). The true character of the political and social structure of Great Moravia remains an open question. It seems to have been a transient society, somewhere between an advanced chiefdom and an early state [1] (Štefan 2011).

The original core of Great Moravia was located in Old Moravia (on the banks of the Morava river in the south-eastern part of today's Czech Republic), in neighboring parts of Slovakia (the so-called Nitra Principality) and probably also Austria (Lower Austria). The foundations of the state structure were laid by the first known representative of the ruling Mojmír dynasty, Mojmír I. (?-846), who, in around 833, banished his rival Pribina from the Nitra region (Poláček 2008b).

Under the rule of his successors, Rastislav (848-870) and Svatopluk (871-894) their territory expanded to Bohemia, Malopolska, Lusatia, and partially also Pannonia and the Tisa river region (Fig. 1). The growing power of Great Moravia, attended by the effort of its Counts to gain international recognition as independent rulers, led the new state more and more frequently into conflict with the East Frankish Empire. The effort to reduce the influence of Franks inspired Rastislav to found an independent Moravian archbishopric, which was finally achieveded by Svatopluk in 880. The last quarter of the 9th century is a golden era for the Great Moravian Empire with advances in territorial expansion, state sovereignty and Christianization. However, after the death of Svatopluk in 894, the power of Great Moravia declined. Moravia, weakened by internal quarrels and wars with recently annexed territories battling for independence and against the Franks, finally succumbed to the invasion of the Magyars in 905-906 (Měřínský 2006; Poláček 2008b; Třeštík 2001).

The collapse of Great Moravia is a fascinating example of a thriving Early Mediaeval empire experiencing a sudden decline over a very short period of time. This downfall of the state structure was accompanied by the reduction of settlement density in the region (Hladík 2014). But the dark age of disintegration and chaos did not last very long –

[1]The discussion on the issue of „statehood“ of Great Moravia is still open to debate. For more details see e.g. Macháček (2012). For our purposes the term „state“ will be used when referred to Great Moravian constitution.

perhaps only two or three generations. The first signs of revival are evident as early as in the 970s (Macháček and Videman 2013). Moravian society then regenerated completely during the course of the 11th century, albeit on an entirely different qualitative level, with new elite and better prospects for further development. Population movement to the north is supposed, where later the new center was established in Olomouc (Hladík 2014; Wihoda and Macháček 2013).

Fig. 1. Extension of Great Moravia and neighbouring European empires in the latter third of the 9th century and the location of Mikulčice center, modified illustration according to Poulík (1975), Havelková et al. (2010) and Kaupová et al. (2014).

2.2 The socio-economic and political structure of Great Moravia

For the Great Moravian era, the high increase of the number of settlements as well as the emergence of new settlements types (centers of crafts, strongholds) is documented, which suggest strong population growth together with an increased socio-economic stratification of society (Hladík 2014).

Because of the scarcity of findings from the pre-great Moravian era (2/2. of the 7th and the 8th century it is not possible to detect the real beginnings of this differentiation (Hladík 2014; Měřínský 2006). In each case, archaeological evidence as well as written sources suggest significant proprietal and social stratification of Great Moravian society. Aside from the elite classes (dukes and nobles) and a group of free tenants, there were also parts of the population living in some form of dependency. Though slaves are not supposed to have played an important role in the Great Moravian economy, their existence is described in terms of people with no rights who could be sold. The most numerous population group – peasants – probably gradually became legally dependent on the ruler, to whom they owed labor duties as well as the liability to pay taxes (Havlík 1978; Poláček 2008b).

2.3 Christianization

Christianity extended into Moravia no later than at the beginning of the 9th century from the East Frankish Empire. During its initial phases, however, the Christianization most probably involved only the narrow group of elite classes. Moravia fell under the competence of the bishop of Passau, which led the country to be under the strong cultural as well as political influence of the Frankish Empire. As stated earlier, it was the effort to reduce the influence of Franks that motivated the request of Rastislav for an independent mission from the Byzantine. In 863 this task was undertaken by two brothers, Cyril (Constantin) and Methodius. Their missionary activities were based on the translation of the Bible and other liturgical texts into the Slavic language, with the aid of the newly created so-called glagolic alphabet. Methodius later, in 879, became the first archibishop for Moravia and Pannonia. Even so, the schism between the Eastern and Western Christian church persisted and even deepened under the rule of Svatopluk. After the death of Methodius (885) Slavic clerics was banished from Moravia and Latin clerics restored (Betti 2013; Měřínský 2006; Poláček 2008b; Poulík 1978).

Though there are no doubts about the huge advance of Christianization through the 9th century, the question of how the Christian faith affected the quality of lives of

Moravians is still difficult to answer. Archaeologically, the Christian influence seems to impact the proportion of pre-Christian customs, including the burial of gifts with the dead, which diminished during the 9th century under the influence of Church prohibition (Dostál 1966; Klanica 1985; Poláček 2008b).

When focused on nutrition, fasting rules imposed by the church may have influenced the diet of the Christianized population by the increased consumption of fish since 9th century Church imposed fasting rules prohibited the consumption of meat on many occasions (Bartoňková et al. 1971). Nonetheless, we may hypothesize, that the pressure to abide to new rules was higher in Great Moravian power centers, especially within elite classes, and also that it was intensified within the 9th century (Poláček 2008b).

The church organization survived the fall of Great Moravia, though there exist certain records documenting a partial resurgence of paganism (Poláček 2008b) in the 10th century. The late Hillfort phase is then characterized by the deeper establishment of Church authority, manifested among others by the further reduction of grave goods, represented mainly by temple rings and coins in 11th century graves (Unger 2006).

2.4 Urbanization

The growing complexity in Moravia between the 8th and 9th centuries involved the rise of extensive centers of a proto-urban type which fulfilled all the basic central functions as centers of political power, of clerical and economic authority, of crafts, trade and learning. They were probably not too much different from their counterparts in Western and Northern Europe (Herold 2012; Macháček 2013a; Štefan 2011).

As of now, we know of at least 30 fortified settlements in the territory of Great Moravia. From this group, several strongholds (Mikulčice, Uherské Hradiště, Nitra) stand out due to their exceptional size, concentration of churches and findings of extraordinarily rich graves. These are supposed to have been the main power centers of the state, though the residence of either a Prince or archbishop have not been proved unequivocally (Poláček 2008b).

In the area of South and South-eastern Moravia, power centers are typically situated in flood plains: on the river banks or isles, either on sand banks rising from alluvial plains or on the slightly elevated river terraces. However during the 9th century the growing settlements expanded into the lower, previously flooded areas (Macháček et al. 2007; Poláček 2001; 2008b).

It is assumed that the densely populated agglomerations were not autarchic and could not sustain themselves without their hinterlands which catered for their needs in terms of food and other important raw materials. The current state of research shows that conspicuous accumulations of contemporary settlements formed in the vicinity of the early mediaeval centers (Hladík 2014; Poláček 2001).

The political and military collapse of Great Moravia at the beginning of the 10th century was followed by the decline of central agglomerations (or even the destruction of the main power centers, most of which were never restored) and a sharp drop in their population numbers (Hladík 2014). The regeneration of the society during the 11th century coincided with a new development in the settlement structure. The not very viable bi-modal model of territorial government, with oversized proto-urban super-central places on the one hand and agricultural settlements in their hinterland on the other, were supplanted by a more complex structure (Lozny 2004). The new sub-centers or second-level central places contributed to increasing population density in peripheral regions and to more effective land exploitation.

2.5 Natural conditions

The expansion of the Great Moravian Empire falls at least partially at the beginning of the Medieval warm period: a period of mild and stable weather which expanded the growing season and resulted in higher productivity of the cultivated land, thereby supporting population growth. The beginnings of this warm period are set between the years 800-900 (Svoboda et al., 2003, Hladík, 2014). Svoboda et al. (2003) date the real beginnings of this period in the Central European area to the year 875, after the series of extraordinarily cold and hungry years. This corresponds to the second half of the Great Moravian period and so the era of its greatest expansion would have been characterized by favourable climatic conditions.

In the Great Moravian period, settlement structure in the area of South and South-eastern Moravia was configured by the main waterways, with the important power centers typically situated on flood plains. Due to the exceptional role of flood plains in Great Moravian settlement strategy, one should pay more attention to the environmental parameters of these areas. In the 8th and 9th century, flood plains were not regularly flooded and their vegetation was characterized by tough woodland with a predominance of oak, elm and ash. The immediate surroundings of settlement agglomerations had probably a park-like character with relatively open forests and various large areas of pastures and meadows, offering sufficient supplies of water and wood as well as good opportunities for fishing and herding. Recently, the existence of fields in close proximity to proto-urban centers has been documented, suggesting the engagement of at least some groups of their inhabitants in agricultural production (Dresler and Macháček 2008; Látková 2015; Macháček et al. 2007; Opravil 2000; 2003; Poláček 2008b).

Local climatic reconstruction in the area of the core of the Great Moravian Empire links the beginnings and the full expansion of Great Moravia to the relatively dry climate, while the end of the 9th and the most of the 10th century is characterized by higher precipitation (Macháček et al. 2007; Poláček 2001). There is also some evidence of climatic change on a global scale sometime during the 10th century – the time of the decline of not only Great Moravia but also of the Frankish Carolingian Empire, the Chinese T'ang dynasty and the Mayan civilization (Macháček 2013b).

The climate change must have had a tangible effect on Great Moravian society, especially its over-sized centers located in the middle of the bottomlands. Problems caused by floods are reflected in archaeological field situations from the 10th century. The water logging of the surrounding country caused many problems - transport, sanitation, epidemiological and subsistence. The unprotected and lower-situated parts of the area became almost uninhabitable. This is an aspect which should be taken into account when discussing the demise of the major central places as well as of the whole of Great Moravia, whose existence was in many ways (economic, military, political and cultural) interlinked with them (Macháček 2013a; b).

It seems that during the 10th and 11th centuries the settlement pattern adapted to these natural threats. The settlements, including the newly-founded centers, moved to higher altitudes towards the margins of the bottomland or away from the bottomland altogether (Macháček 2013b). Once again, this is not a purely local phenomenon but one documented also in other parts of the Central European region – such as medieval Germany (Schneeweiss and Schatz 2014). The 11th century is generally considered the period of culminating climatic optimum in the Central European context (Svoboda et al. 2003).

2.6 Archaeological perspectives on Great Moravian diet

The analysis of plant macroremains shows that in the Great Moravian period common wheat (*Triticum aestivum*) was predominant among cereals in both the centers and hinterland. Findings of millet (*Panicum milliaceum*) were frequent in all the contexts, without any remarkable trend regarding the socio-economic role of the site (Dreslerová et al. 2013; Látková 2014a; b; 2015; Opravil 2000; 2003). There is a generally shared assumption, that while the main production area of wheat lay in the hinterland, most of this highest quality bread cereal was grown to satisfy the needs of the higher socio-economic classes of nearby centers while in the lower classes, including rural sites of the hinterland, rye (*Secale cereale*) had a higher importance. Also historical sources link the consumption of wheat to the high socio-economic classes while millet and rye were consumed by the lower classes (Beranová and Kubačák 2010). Foxtail millet (*Seturia italica*) was also known in 9th century Moravia. Leguminous plants are documented both in centers and hinterland but their findings were rare (Dreslerová et al. 2013; Látková 2014a; b; 2015; Opravil 2000; 2003).

After the fall of Great Moravia, the spectrum of cultivated crops changed. The importance of wheat declined in favor of rye and especially millet, which are both less demanding cereals able to stand worse natural conditions (e.g. soils of worse quality, periods of drought) and to produce more reliable yields (Beranová and Kubačák 2010; Dreslerová et al. 2013). This feature is not restricted to Moravia but is evident also in other areas of today's Czech Republic (Čech et al. 2013).

However the testimony of palaeobotanical sources is not unequivocal. The most complete and comprehensive study of plant macroremains, performed in Mikulčice by E. Opravil (summarized in 2000; 2003), stress the clear dominance of wheat in the area of the Mikulčice agglomeration, followed by rye and barley, while millet is represented by scattered findings of relatively low frequencies and its importance in agricultural production is, according to Opravil, “difficult to estimate”. However most recent analysis of plant macroremains in Mikulčice suggests the much higher importance of millet (Látková 2014b).

Historical sources on the consumption of millet are scarce and indecisive. While generally, millet is supposed to be consumed by the poor and during famine periods (Adamson 2004), local sources mention millet porridge to be a prestigious meal of the elite groups (Beranová 2005).

Compilation of the most recent research of Great Moravian agricultural production suggest that a mainly socio-economically motivated difference in cereal use may lie rather in the different importance of wheat versus rye, i.e., different cereals used for bread production (Látková 2014a; b; 2015), than in the consumption of millet eaten in the form of porridge.

Although there are large collections of excavated animal bones, the archaeozoological evidence for the Great Moravian diet is limited. Especially in Mikulčice, where the largest collection of animal bones was recovered, its representativeness suffered from the lack of interest during the first excavation seasons, during the years 1954-1962, when only some randomly chosen animal bones were collected and then stored in an inappropriate manner. Subsequently only the portion of material recovered in the 1980s or later provided a suitable subject for modern archaeozoological research (Mlíkovský 2003).

However, differences in the species spectra as well as slaughter age were noted between different parts of the Mikulčice settlement agglomeration suggesting socio-economic differences, with elite classes consuming more pork and the meat from young animals. Interestingly, the proportion of hunted fauna was low (lower than 4%) even in the supposed residential area of elite classes (Chrzanowska and Januszkiewicz-Załęcka 2003; Chrzanowska and Krupska 2003). This low proportion is similar to that of the hinterland site of Kostice – Zadní hrůd (Dreslerová et al. 2013).

In contrast, while the research is still ongoing, the preliminary evaluation of the archaeozoological material from the Pohansko center shows that the final phase of Great Moravia is linked to the substantial increase in the proportion of hunted fauna (Macháček, personal communication) including high numbers of less common species such as bears and beavers.

The high proportion of hunted fauna is characteristic also of the post-Great Moravian period, comprising up to one third of all osteological material in Kostice at that time. And while the share of hunted fauna gradually declined, it remained relatively high into the 11th and 12th centuries. The growing importance of hunting perhaps came in response to greater demand for meat production, which is also documented by an increased share of pig bones in Kostice (the consumption of pork peaked in the eleventh century when around 60% of the total number of classified bones were from pigs). This phenomenon has been suggested to be connected to the emergence of a secondary center in these locations (Dreslerová et al. 2013).

Concerning fish remains, the only site with published results on numerous assemblages of fish comes from Mikulčice. Though ancient excavation technique again pose a substantial limitation for archaeozoological analysis, a broad spectra of freshwater species have been identified. The most common were findings of carp (*Cyprinus carpio*) (~70% of all findings), followed by catfish (*Silurus glanis*) and pike (*Esox lucius*). Other species: roach (*Rutilus rutilus*), tench (*Tinca tinca*), dace (*Leuciscus leuciscus*) chub

(*Leuciscus cephalus),* ide (*Leuciscus idus*), zander (*Stizostedion lucioperca*) perch (*Perca fluviatilis),* crucian carp (*Carassius carassius*), common rud (*Scardinius erythropthalmus*) and bream (*Abramis brama*) were rare, represented by 5 or less findings. To our best knowledge, there have been no identified remains of marine or anadromous fish (Zawada 2003).

3 STABLE ISOTOPE ANALYSIS IN BIOARCHAEOLOGY

Nitrogen and carbon stable isotope ratios circulate in the biosphere through plants and animals. Their utility in paleo-dietary studies derives from the fact that isotopic signatures of different foods are preserved in the tissue of consumers (Van der Merwe and Vogel 1978; Vogel and Van Der Merwe 1977).

As the term "stable isotopes" clearly indicates, their key characteristic is that they do not undergo radioactive decay. However, relative abundances of stable isotopes of certain elements change as the element is transferred from foods to consumer tissues due to the process known as isotopic fractionation. Isotopic fractionation is caused by the fact that the bonds of lighter isotopes are weaker than bonds of heavier isotopes and break more easily during such events as diffusion and evaporation. Subsequently, during certain chemical reactions, fractionation changes the overall isotope signatures of an initial material and its by-products (Hoefs 2008).

Stable carbon isotope ratios provide information about the ecosystem of a consumer, distinguishing between terrestrial versus marine niches and between ecosystems based on C_3 (adapted for temperate environment) and C_4 (adapted for arid climate) plants. Stable nitrogen isotope ratios reflect an organism's trophic position in the local food web, distinguishing between carnivores, omnivores and herbivores. Subsequently, $\delta^{15}N$ values are used to assess the relative importance of plant and animal products in human diet (Ambrose and Norr 1993; DeNiro and Epstein 1978; 1981; Lee-Thorp 2008; Minagawa and Wada 1984; Schoeninger and DeNiro 1984).

The isotopic value of a particular sample is expressed as a δ value: comparison of the ratio of the two isotopes of an element to a standard. The δ is expressed in units per mil (‰) and is calculated by the following equation:

$$\delta = \left(\left(\frac{\text{Rsample}}{\text{Rstandard}}\right) - 1\right) \text{x} 1000$$

Equation 1

where R is the ratio of the heavier isotope to the light isotope, e.g. $^{15}N/^{14}N$ (Hoefs 2008).

3.1 Nitrogen stable isotopes

For nitrogen significant fractionation is observed at each stage of the food chain. With heavier isotopes discriminated against, $\delta^{15}N$ values are heavier at each step, a phenomenon termed the “trophic level effect”. This is caused by the fact that during metabolic processes, the lighter isotope ^{14}N breaks down more easily than ^{15}N and is preferentially excreted with urea. Generally, the isotopic enrichment at each step is suggested to be between 3 and 5‰ (Ambrose and Norr 1993; DeNiro and Epstein 1978; 1981; Minagawa and Wada 1984; Schoeninger and DeNiro 1984).

However, some studies indicate a higher variation between +1.5 and 6 ‰, depending on both species and ecosystem (Caut et al. 2009). O'Connell et al. (2012), suggesting that for human collagen tissue the diet-collagen offset is around 6‰ which would mean that animal protein intake has been overestimated in many studies of prehistoric and historic populations. However, this study does not aim to the exact estimation of the percentage of animal protein but rather to the comparison of isotopic values between distinct sub-groups of a population.

Potentially problematic in the dietary reconstruction based on stable isotope analysis of nitrogen may be the effect of legume consumption. Legumes are capable of fixing atmospheric nitrogen without fractionation via symbiotic bacteria; therefore the $\delta^{15}N$ values of legumes are close to 0‰. When consumed in higher portions, they may be capable to blur at least partially the effect of animal protein consumption. The real impact that legumes may have on the $\delta^{15}N$ values of individuals is still not well understood. (Klepinger 1984).

Another limitation of dietary reconstruction based on nitrogen isotopic data is that, while bringing important information on the proportion of animal protein, it is not able to distinguish between meat and dairy products from the same animal (O'Connell and Hedges 1999).

Also in the aquatic ecosystems (either freshwater or marine), $\delta^{15}N$ reflects primarily the length of the food chain. Because generally there are longer food chains in these environments, nitrogen isotopic values of fish and aquatic mammals are usually higher than those of the terrestrial animals, which could be used to estimate the importance of aquatic resources in the diet of past populations (Finlay and Kendall 2007; Fuller et al. 2012b). However, high variation of fish isotopic data was observed (Fuller et al. 2012b) even within a single species. Beside the natural sources of $\delta^{15}N$ variation in water bodies (France 1994) this variability may be linked also to the age-related changes in foraging behavior. As predatory fish grow larger with age, they may catch a wider variety of prey, including other fish, amphibians, molluscs, and even small mammals, which means $\delta^{15}N$ values of fish of the same species increase with age and size (Sweeting et al. 2007). Subsequently, systematic $\delta^{15}N$ variations occur not just between species, but between niches as well (Sherwood and Rose 2005), which may bring complications into the dietary reconstruction.

3.2 Carbon

As in the case of nitrogen, isotopic enrichment occurs at each stage of the food chain. For carbon, however, this enrichment is much lower: approximately +1‰ (Ambrose and Norr 1993; DeNiro and Epstein 1978; 1981; Minagawa and Wada 1984; Schoeninger and DeNiro 1984).

In the terrestrial ecosystems, atmospheric CO_2 ($\delta^{13}C$ of −8‰) is the only source of inorganic carbon for plants. For $\delta^{13}C$, terrestrial plants fall into two main categories, based on different photosynthetic pathways for the uptake of carbon: C_3 plants dominate in a temperate climate. The average $\delta^{13}C$ value of C_3 plants is around −27‰ with a range of about 15‰ depending on light intensity, temperature, humidity, moisture and recycling of CO_2. The C_4 photosynthetic pathway is, on the other hand, promoted by heat, water limitation and/or salinity in warm regions. This type of photosynthesis prevents excessive photorespiration, enhances water-use efficiency and lowers isotopic fractionation. As a result, the average $\delta^{13}C$ value of C_4 plants is about −13‰, with a smaller range of values (Farquhar et al. 1989; Marshall et al. 2007; O'Leary 1981; Sage 2004; Smith and Epstein 1971). Economically important C_3 plants are mainly cereals including wheat, barley, oats and rice as well as all root staples such as potato, manioc and yam; of C_4 plants maize, sorghum cane sugar and millet are the most imported members of this group (Lee-Thorp 2008). For the sake of completeness, a third class of plants should be mentioned. This group uses a crassulacean acid metabolism (CAM) to fix carbon. This strategy enables some plants to switch between the C_3 and the C_4 carbon fixing pathways in response to climatic shifts, which results in carbon isotopic values which are between the C_3 and C_4 plant ranges (Hoefs 2008).

Besides the use of stable carbon isotopes in identifying C_3 vs. C_4 plants consumption, it could also be a useful tool to explore marine resource utilization. The distinct isotopic signal of marine resources comes from the distinct sources of carbon: the major source of carbon in these ecosystems is dissolved inorganic carbon which in ocean waters exhibits an average $\delta^{13}C$ value of about 1.5‰ (Hoefs 2008). Organic matter (including algae and detritus) is another source of carbon with substantially different $\delta^{13}C$ values (ranging between –22.0‰ to –18.5‰) (Hoefs 2008). As a result of this, marine fish $\delta^{13}C$ values can range from approximately –19.0‰ to –11.0‰ (Barrett et al. 2008). However, we do not suppose the marine resources consumption to be of high importance in the context of this study.

In the Great Moravian context, much more relevant could be the isotopic variation in freshwater resources. Carbon isotopic values in freshwater ecosystems are highly variable. The main sources of inorganic carbon in fresh waters are atmospheric CO_2, carbonate rock dissolution and respiration and each has a distinct $\delta^{13}C$. Carbon isotopic values in the riverine ecosystem are defined by the proportion of allochtonous (terrestrial) and autochtonous sources. This proportion changes along the river course along with changing canopy shading, turbidity etc. with substantial heterogeneity at all spatial scales, and considerable temporal variation (Finlay and Kendall 2007). Also important is the trophic status of the water bodies (e.g. oligotrophic, mesotrophic, eutrophic, hypertrophic). As another important factor, widely diverse habitats are hydrologically connected throughout the drainage network, enabling both fluvial transport of resources and movement of organisms, which may play important and often definitive roles in carbon isotopic variation (Finlay and Kendall 2007; Grey et al. 2001; Gu et al. 2010).

3.3 Non-dietary sources of carbon and nitrogen isotopic variability

It has been demonstrated, that both carbon and nitrogen isotopic values vary significantly across time and space (Goude and Fontugne 2016; Nardoto et al. 2006; van Klinken et al. 2002). This results from a number of factors which will be discussed in detail in the following section. From this, the necessity arises to relate actual isotopic values measured in human bone to the environmental baseline. For this reason, animal bones are usually used in an archaeological context.

3.3.1 Climate

Both carbon and nitrogen isotopic ratios may vary due to the effects of temperature and humidity. In the case of carbon, it is due to the effect of these factors on photosynthesis (van Klinken et al. 2002). From different climatic factors (temperature, humidity, altitude, latitude), it was humidity, which proved to have the strongest impact of carbon isotopic values, indicating stomatal constraints on leaf gas-exchange, mediated by water supply, are the dominant control (Diefendorf et al. 2010). This may be of special importance for this study which deals partially with flood-plain ecosystems, where the humid environment may result in more negative carbon isotope ratios.

Hot, arid climate was also suggested to amplify the isotopic fractionation between trophic positions due to physiological responses to heat stress. To conserve water, many organisms are capable of concentrating the urinary urea as well as increase the excreted amount of urea. Then elevated excretion of ^{15}N-depleted urea must be balanced by the retention of ^{15}N-enriched nitrogen, resulting in body tissues more enriched than normal (Ambrose 1991). However experimental studies have not yet validated this hypothesis (Ambrose 2002).

3.3.2 Canopy effect

For the carbon isotopic values, substantial variation was observed between open versus forested areas. This is due to the fact that, in dense forest, tree-canopies prevent the natural admixture between atmospheric CO_2 and CO_2 originating from the decay of organic matters. So this ^{13}C-depleted CO_2 of organic origin is recycled. This, together with low light intensities and water surfeit, cause δ^{13}C values of plants and animals occupying closed-canopy habitats to be less ^{13}C-enriched than those outside the canopy (Farquhar et al. 1982; Lynch et al. 2008; van der Merwe and Medina 1989; 1991). The canopy effect appears to be most pronounced in tropical and mid-latitude forests (Kohn 2010; van der Merwe and Medina 1991), but also has been reported for temperate and boreal forests (Drucker et al. 2008; 2010; but see Stevens et al. 2006).

This has resulting consequences for the dietary analysis of past populations. Plants grown, and subsequently animals foraging, in dense forests show lower carbon isotopic values than those from open fields (Bocherens et al. 1995; Cerling and Harris 1999; Fizet et al. 1995; Krigbaum 2003; Lynch et al. 2008). Subsequently hunted wild species (foraging more in forested areas) may show different isotopic values than domestic species (in which more open areas are usually used for pasture) (Lynch et al. 2008; Reitsema et al. 2013).

3.3.3 Fossil fuel emission

Since the industrial revolution, fossil fuel emissions have increased enormously. Being isotopically light, these have caused an overall shift in carbon isotopic values of atmospheric CO_2 from pre-modern times (Marino and McElroy 1991). As a consequence, when making a comparison between modern and archaeological plants and animals, a correction factor of -1.5‰ should be applied to archaeological samples (Kellner and Schoeninger 2007).

3.3.4 Husbandry and agricultural practices

The manuring of agricultural fields can cause plants to be significantly ^{15}N-enriched relative to unfertilized plants (Bogaard et al. 2007; Fiorentino et al. 2012; Choi et al. 2003; Kanstrup et al. 2012; Szpak et al. 2012). This is because the lighter isotope (^{14}N) in manure is preferentially lost as gaseous ammonia during ammonia volatilization, a process associated with a large fractionation (Mizutani et al. 1985). Plants take up nitrogen from the remaining ^{15}N enriched manure, resulting in higher $\delta^{15}N$ ratios throughout the food-web. In an experimental study, Bogaard et al. (2007) demonstrated that plants grown on manured soils exhibit $\delta^{15}N$ values of more than 7‰, compared to non-manured plants from the same field which exhibited grain values lower than 1‰.

Stable nitrogen isotope signatures of plants and the animals eating them may also indicate that swidden agriculture was used in the past, providing nuanced information about land management strategies (Bogaard et al. 2007; Commisso and Nelson 2008; Grogan et al. 2000). Fires raise the baseline $\delta^{15}N$ in ecosystems because they remove top-soils which are low in ^{15}N due to generations of selective uptake by plants (Grogan et al. 2000). Plants growing on land recovering from a fire take up nitrogen from the remaining soils and in that way a higher proportion of ^{15}N enters the food-web. Moreover, plants recovering in burned areas take up fewer nitrates (which are isotopically depleted) than do plants in unburned areas. For the same reason, ploughing can also increase the $\delta^{15}N$ of the source nitrogen available for plants (and subsequently of grazing animals) by mixing surface and deep soils (Reitsema et al. 2013). Grazing intensity also has been shown to influence the $\delta^{15}N$ variation in plants and subsequently through the food-web (Han et al. 2008). It has been demonstrated that the effects of the impact of these factors on the $\delta^{15}N$ values of soils and plants are distinguishable even hundreds of years after the fact (Commisso and Nelson 2006; 2007; 2008; 2010).

Concerning humans, consumption of grain grown on heavily manured soils may therefore lead to the misinterpretation of isotopic data, who then appear to have consumed more animal protein than was actually the case (Bogaard et al. 2007). This effect can be at least partially controlled by 'calibrating' human isotope values with those of animals that likely consumed plants from the same soil.

Husbandry practices may also influence the isotopic values of domesticated animals and consequently also those of the people consuming them. The proportion of plant and animal foods may differ as husbandry changed, along with growing sedentarization, settlement density and urbanization. In these contexts, where animals and humans share close quarters, animals (especially some species) more often consume scraps of meat, offal or dairy products from among human foods and/or human and animal waste (Fuller et al. 2012a; Reitsema et al. 2013). This is often reflected in the isotopic values of fowl, dogs and, in some contexts, also pigs. Pig breeding techniques changed substantially during the Middle Ages in tandem with progressing urbanization. Due to the fact that they could be kept near a household, with little space required, they were especially suitable to feed agglomerated urban populations as opposed to large-bodied grazing cattle or wild animals, the hunting of which was restricted by the developing socio-political nobility (Hammond and O'Connor 2013).

3.3.5 Physiology – nitrogen balance

When leaving aside specific disorders, which may have the potential to influence human isotopic values, the most important physiological mechanisms which are suggested to affect human isotopic signatures are the negative and positive nitrogen balance (Reitsema 2013).

Negative nitrogen balance occurs during starvation or nutritional/protein stress. Ingesting less nitrogen than are a body's requirements for basic physiological processes and tissue maintenance results in the catabolisation of body tissues to supply the needed nitrogen. As tissues are broken down and reprocessed, isotopic fractionation (that naturally occurs during the protein metabolism and causes the nitrogen trophic level shift) takes its place, resulting in elevated $\delta^{15}N$ (Gannes et al. 1997).

A positive nitrogen balance, on the other hand, occurs when more nitrogen is ingested for new tissue synthesis than is expelled. Typically this occurs during growth and results in decreased fractionation and thus lower $\delta^{15}N$. As early as the 1980^{s} Minagawa and Wada (1984) suggested the potential effect of growth on nitrogen isotopic fractionation. This would have a great influence on nitrogen isotopic data interpretation because, if true, comparisons of $\delta^{15}N$ could only be made within the same age category (Ponsard and Averbuch 1999).

Numerous animal models have confirmed the influence of a negative nitrogen balance on isotopic values (Barboza and Parker 2006; Boag et al. 2006; Gustine et al.

2011; Hobson et al. 1993; Cherel et al. 2005; Oelbermann and Scheu 2002; Parker et al. 2005). However exceptions may be found and it was therefore suggested that there may be a threshold for the effect on δ^{15}N values. This means that the isotopic change will be detected only if the organism is stressed severely enough (Hatch 2012).

In humans, studies conducted on adults agree on the fact that severe nutritional or physiological stress related to the protein turnover process (in conditions such as osteopenia and anorexia) may increase the δ^{15}N values in tissues (Katzenberg and Lovell 1999; Fuller et al. 2005; Mekota et al. 2006). However, some results also suggest the existence of some threshold with a mild nutritional deficiency not being visible in the isotopic record (Hatch et al. 2006). This is of extreme importance because humans are highly adaptable in their dietary behavior and starvation is usually linked with extreme situations only while moderate nutritional stress is much more common. Some suggest that mild nutritional deficiency is visible only in tissues and substances with rapid synthesis (such as urine) while in slowly growing tissues it is undetectable (Reitsema 2013). In the light of these findings, it seems improbable that the changes in nitrogen balance would influence isotopic values of such a slowly remodeling tissue as an adult human bone. This was confirmed by the study by Nitsch et al. (2010) performed on a 19th century skeletal sample of females with documented parity status. This study did not register any effect of pregnancy on bone isotopic values of females, although this was previously clearly demonstrated in hair samples of modern women (Fuller et al. 2004).

For sub-adults, the impact of stress has been even less explained. Because of the lack of information on human physiology and pathophysiology and its influence on isotopic values (Reitsema 2013) the majority of our information comes from the animal controlled feeding experiments. From those Ambrose (2002) proposes that contrary to the reaction of the mature organism, sub-adults undergoing a period of nutritional stress may slow their growth rate rather than resort to tissue catabolism. This was verified by Kempster et al. (2007) on the sample of growing song sparrows, which under biologically meaningful level of nutritional stress, which has a measurable impact on physiology, growth and development, showed no effect of the feeding regime on either δ^{15}N or δ^{13}C values in any tissue. Williams et al. (2007) mention the potentially competing influence of a positive nitrogen balance when the stress events come during growth (widely discussed in Waters-Rist and Katzenberg 2010).

In humans, for sub-adults, no study has yet demonstrated that enrichment in ^{15}N in children’s tissue could be related to other non-dietary factors. Two studies conducted on sub-adults show neither a change in $\delta^{15}N$ values during growth from early to late adolescence (Waters-Rist and Katzenberg 2010), nor a linear correlation between $\delta^{15}N$ values for children's hair and protein metabolism (de Luca et al. 2012).

3.4 Collagen *vs.* carbonate

In recent years, the isotopic analysis of bone apatite (carbonate) in conjunction with bone collagen has become more common in the bioarchaeological analyses of ancient diets. Thanks to the fact that the isotopic composition of collagen reflects mainly that of dietary protein while the values gained from apatite correspond with the whole diet (Ambrose and Norr 1993), this method theoretically prevents the overestimation of the importance of a high-protein dietary component that is enriched in ^{13}C (e.g., marine fish) and the underestimation of ^{13}C enriched plant foods that are low in protein (e.g., maize or millet) (Harrison and Katzenberg 2003).

The stable isotope analysis of apatite has a potential for paleodiet reconstruction especially when exploring the consumption of one or more C_4 plants against a background of C_3 plants and C_3-consuming animals or when the consumption of marine resources against a background of C_3 terrestrial foods is in issue. This has a particular importance in the case of protein-poor foods (such as maize) that may be reflected even when consumed in small amounts untraceable in bone collagen (Harrison and Katzenberg 2003).

The difference between the $\delta^{13}C$ value of the diet and bone apatite is 9.5‰ in controlled feeding experiments regardless of the $\delta^{13}C$ values of dietary protein and energy sources (Ambrose and Norr 1993; Tieszen and Fagre 1993). On the contrary, because the dietary protein is routed preferentially to collagen, the spacing between $\delta^{13}C$ values of collagen and the $\delta^{13}C$ of diet will change in relation to the $\delta^{13}C$ values of dietary protein (Ambrose and Norr 1993). As a result the spacing between the $\delta^{13}C$ values of bone apatite and bone collagen ($\Delta^{13}C_{ap\text{-}coll}$) can thus reveal important information about the kinds of protein in the diet. Small $\Delta^{13}C_{ap\text{-}coll}$ indicates that the protein portion of the diet is more enriched in ^{13}C than the diet as a whole, suggesting that the protein was from a marine or C_4 source. Large differences indicate that the protein source was lighter than the whole diet, such as protein from terrestrial animals or freshwater fish (Ambrose and Krigbaum 2003).

Beside this, in the specific context where the $\delta^{13}C$ values of macronutrients do not differ substantially, $\Delta^{13}C_{ap\text{-}coll}$ can provide useful information on the trophic position of an organism. Herbivores obtain energy from carbohydrates whereas carnivores obtain dietary energy primarily from lipids in their prey, which are isotopically depleted compared to the collagen of their prey. As a result, the difference between the $\Delta^{13}C_{ap\text{-}coll}$ of carnivores is thus smaller than that of herbivores (Ambrose and Krigbaum 2003).

However, Kellner and Schoeninger (2007) suggested that the absolute value of $\Delta^{13}C_{ap\text{-}coll}$ is not specific to any particular combination of protein or whole diet which minimizes its predictive power for diet reconstruction. Using the previously published data on controlled feeding experiments, these authors created an innovative model of combining collagen and apatite isotope data that is argued to be more accurate than using collagen, apatite, or collagen-apatite spacing relationships alone in reconstructing past diet. Because the experimental animals in this study are modern, a correction of 1.5‰ needs to be subtracted from archaeological values for comparison because of the Suess Effect (Marino and McElroy 1991)

Finally, Froehle et al. (2012) developed the model using the discriminant functions operating with the $\delta^{15}N$ value, and in addition with the $\delta^{13}C_{ap}$ and $\delta^{13}C_{coll}$, in order to distinguish between the C_4 and marine based sources of protein.

Although this study is primarily based on the isotopic analysis of bone collagen, the $\delta^{13}C$ of bone apatite was measured in a small sub-sample of 30 individuals in order to confirm the results on bone collagen and to check for potential slight differences in C_4 consumption that may not be obvious when using $\delta^{13}C_{coll}$. Since substantial consumption of marine resources could not be reasonably supposed, the model developed by Kellner and Schoeninger (2007) was applied.

3.5 Sulphur

Sulphur isotopic ratios are predominantly influenced by local geology and hydrology (Nehlich 2015). Also climatic influences, such as wind direction and the amount of rainfall, can influence local sources of bio-available sulphur. Local inorganic sulphur, which is bound into biomolecules by plants, is a mixture of rainwater, groundwater, stream water and the gaseous sulphur from the atmosphere (Nehlich 2015; Nriagu et al. 1991). Once taken up by plants and animals, the sulphur is incorporated into the amino acids (methionine and cysteine) and protein (Nielsen et al. 1991). During this process only a small fractionation occurs and subsequently the $\delta^{34}S$ value change only slightly along the food chain and the isotopic signal of the local environment is maintained in the organic tissues (Hobson 1999).

Stable isotope analysis of sulphur proved to be a useful tool to uncover both the dietary practices and migration trends in past populations, especially when the consumption of marine diet or migration from or into coastal areas is in issue (for a detailed review see Nehlich 2015). In inland areas (such as Central Europe) the huge variability of the $\delta^{34}S$ value, depending on local water sources and geological conditions, represents a big potential to tease out more the often problematic issue of freshwater fish consumption (Nehlich et al. 2010; Richards et al. 2001; Sayle et al. 2013). The basic idea of this analysis is based on the simple premise that riverine ecosystems, with an input further away from the research area, dispose of a much broader range of sulphur sources and, as such, make a good contrast to terrestrial ecosystems in a given area which bear a more local isotopic signal. Therefore, under favorable conditions, the sulphur isotope composition may allow us to distinguish between the dietary source coming from freshwater *vs.* terrestrial ecosystems.

In case of flood plain-situated Great Moravian centers, special attention should be paid to the fact that riverine sulphate can also be found on the riverbanks and floodplains and, therefore, can influence the sulphur isotopic composition of the surrounding landscape (Fry 2002; Nehlich et al. 2011). This means that plants and animals from floodplain areas will show isotopic values in between those typical for local terrestrial and aquatic organisms. This may theoretically help to distinguish between animals grown locally (in the vicinity of floodplain located centers) and those transported from the hinterland.

The utility of sulphur in studies of freshwater fish consumption is highly dependent on local geological and hydrological conditions. In some contexts (e.g. in areas with a complex surface geology) it is not possible to distinguish between freshwater and terrestrial ecosystems (Privat et al. 2007). In some rivers the range of $\delta^{34}S$ values measured in specific fish species is ~5‰ but in other rivers fish $\delta^{34}S$ values had a range of 35‰ (Hesslein et al. 1991). To predict the degree of overlap between freshwater and terrestrial species cannot be reliably effectuated at any archaeological site (Privat et al. 2007). That is why the isotopic analysis of human samples should always be preceded by a pilot study effectuated on animal samples.

3.6 Isotopic analysis of breastfeeding

Isotopic fractionation occurring at each level of the food chain allows us, among other things, to determine the timing of weaning as the greatest dietary change of an entire life. In newborns, isotopic composition of tissues is roughly similar to those of the maternal organism (Fogel et al. 1989). During breastfeeding, infants derive their nutrition from their mother's protein. As a results of isotopic fractionation (the trophic level effect), they exhibit an elevation of both $\delta^{13}C$ and $\delta^{15}N$ above maternal values. Once the process of weaning starts, the isotopic values of newly formed tissues drop continuously with decreasing breast milk intake (Fogel et al. 1989; Fuller et al. 2006b). Fuller et al. (2006b) suggested that during weaning, the $\delta^{13}C$ values decline to maternal levels more rapidly than the $\delta^{15}N$ values. This quicker decrease is suggested to be caused by the combination of two mechanisms: firstly, due to the smaller enrichment of 1‰ it takes less time to return to the maternal values. And secondly, commonly used weaning foods are generally rich in carbohydrates so they primarily influence the carbon pool of the infant while nitrogen is still primarily derived from breast-milk protein. Due to this, Fuller et al. (2006b) suggested that carbon isotopic values can be used to track the introduction of the first solid foods into the diet, whereas $\delta^{15}N$ values better reflect the length of breast milk consumption. It has to be stressed here, however, that the validity of this assumption would depend on the true nature of the consumed weaning foods.

The most recent approach to isotopic analyses of breastfeeding and weaning behavior uses the strategy of intra-individual sampling, with samples taken from different mineralized tissues (i.e., bone *vs.* tooth) (Herrscher 2003; 2013; Howcroft et al. 2012), from different parts of bone (Waters-Rist et al. 2011), or from serial sections of dental tissues (Beaumont et al. 2013; Eerkens et al. 2011; Fuller et al. 2003; Henderson et al. 2014; Howcroft et al. 2012). This approach has a great advantage in comparison to the routinely used cross-sectional model, where the age of weaning is averaged out across the whole population (e.g. Dupras et al. 2001; Fuller et al. 2006a; Jay et al. 2008; Pearson et al. 2010; Prowse et al. 2008; Williams et al. 2005 and many others). It removes the confounding factor of intra-population variability in diet among lactating females as well as their children and allows us to determine the exact feeding status of each infant (Eerkens et al. 2011; Waters-Rist et al. 2011).

This study is based on the sampling strategy developed by Herrscher (2003). Sampling different mineralized tissues (bone *vs.* tooth dentin), it works with a combination of dietary signals from different periods of an individual's life. Bone undergoes constant turnover, so that its isotopic composition reflects the average diet for some period prior to death. The length of this period is dependent on the bone turnover rate and consequently is highly variable and affected by different factors such as sex, nutritional status, physical activity and, especially, the age of an individual (Hedges et al. 2007; Martin and

Armelagos 1985; Seibel 2003). By contrast, dentin does not remodel, so its isotopic composition retains information regarding diet at the period of tooth development throughout life (Balasse et al. 1999; Richards et al. 2002). Thus, after the initiation of breastfeeding, the $\delta^{15}N$ of newly formed dental tissues reflects the full trophic level effect in a short time, while the bone $\delta^{15}N$ increases much more slowly along with the growth of bone and replacement of prenatally developed tissue. The same principle applies during weaning when the dental $\delta^{15}N$ value drops much more rapidly to adult values (Herrscher 2003). In our study, samples were taken from the bone at the mandibular basis and from the apical end of the developing dental root. With regard to a certain indeterminable period that the metabolic nitrogen pool takes to equilibrate with the diet, isotopic values of a dental root sample reflect the diet immediately before death (Balasse et al. 2001) while a bone sample retains dietary information from a more distant past.

With this approach, it is possible to estimate the nutritional status of each child on the basis of the relative nitrogen isotopic differences between tooth and bone samples ($\Delta^{15}N_{t\text{-}b}$). In case of a positive $\Delta^{15}N_{t\text{-}b}$, higher $\delta^{15}N$ in a tooth suggests that the particular child was breastfed at the moment of its death. Negative value (higher $\delta^{15}N$ in bone) indicates that weaning took place some time before. However, weaning is not an abrupt change but a continuous process starting with the first introduction of supplementary food and ending with the complete cessation of breastfeeding (Pearson et al. 2010; Wilson et al. 2006). It should be kept in mind that using this sampling strategy, we are not able to distinguish these two exact moments in the child's life so our terms "breastfed" and "weaned" have to be interpreted with caution rather in the sense of "child still consuming breast milk substantially" and "child whose milk consumption decreased substantially" (Kaupová et al. 2014).

3.7 Sample diagenesis and contamination

The quality of bone extracts is crucial to the reliability of stable isotope palaeodietary analysis and depends strongly on the extent of diagenetic degradation, contamination and the type of extraction method (van Klinken 1999).

Depending on the character of the burial environment, collagen can be more or less easily degraded by breaking (hydrolization) of peptide bonds amongst its constituent amino acids (Collins et al. 1995). Subsequently, these larger or smaller peptides may be leached from the bone in burial environment but also during chemical extraction of collagen. Collagen may also be digested by the microbial attack from the soil (Nielsen-

Marsh and Hedges 2000a). Additional change to isotopic values may be caused by lipids which may remain in bone after collagen decays. Being relatively depleted in ^{13}C, differential preservation of lipids can cause $\delta^{13}C$ ratios from the non-mineral fraction of bone to be deceptively lowered (Ambrose 1990).

In most cases, the collagen alteration is preceded (and initiated) by dissolution of the mineral phase which exposes collagen to biodegradation (Collins et al. 2002). Analogically younger (less mineralized) collagen is more soluble than older collagen (Bell et al. 2001), and degradation affects it more easily.

The background contamination can also affect isotope ratios in bone organic matter and can be in situ (humic contaminants such as bacteria and fungi), or lab-derived. That is why ultrafiltration or soaking in sodium hydroxide and/or methanol are common phases of collagen extraction, removing both lipids and humic contaminants (Ambrose 1990).

To determine the quality of preservation of bone collagen a set of criteria has been developed. The easiest and generally used indicator of collagen preservation is the collagen yield, which is ~22% in fresh bone. Other preservation criteria include overall carbon content in collagen (% carbon), overall nitrogen content (% nitrogen) and the atomic ratio of carbon to nitrogen (C:N). Generally, degraded samples are expected to have variable (usually lower) % C, variable (but usually higher) C:N ratios, variable (but mostly more negative) $\delta^{13}C$, and mostly higher $\delta^{15}N$ values. For contaminated samples higher % C and C:N ratio and more negative $\delta^{13}C$ values are typical, however it depends on the source of contamination. A low percentage of carbon (as well as nitrogen) suggests contamination from inorganic substances (such as lingering apatite or salt residues coming from the extraction solution). A high percentage of carbon, on the other hand, suggests the presence of organic carbon (Ambrose 1990; DeNiro 1985; van Klinken 1999).

Acceptable ranges for these parameters were reported by Ambrose (1990), DeNiro (1985) and van Klinken (1999) and are presented in Table 1.

TABLE 1. Acceptable ranges of collagen quality indicators in the stable isotope analysis of carbon and nitrogen

Quality indicator	**Acceptable ranges[a]**
Carbon content (%)	>13 (13-47)%
Nitrogen content (%)	>5 (5-17)%
C:N ratio	2.9-3.6 (3.1-3.5)
Collagen Yield	> 1 (5-28%)

[a] recommended ranges differ slightly among different authors. In this study, more strict criteria were used in all the cases, except for collagen yield, where the threshold of 1% was recommended for the skeletal material of European origin (van Klinken 1999).

Additionally, correlation between collagen quality indicators and isotopic values may tell us about significant sample diagenesis or contamination. To minimize this effect, samples with extreme values in their preservation criteria may be excluded from the data-set until a significant correlation disappears, regardless of whether they fall within or outside the accepted range (Garvie-Lok 2001; Reitsema 2012b).

The quality criteria applied in stable isotope analysis of sulphur were developed by Nehlich and Richards (2009). Due to the distinct amino-acid composition of fish bone collagen, which includes a higher percentage of methionine and thus a higher amount of sulphur, they are specific for mammalian and avian *vs.* fish samples (Table 2).

TABLE 2. Acceptable ranges for collagen quality indicators in the stable isotope analysis of sulphur

Quality indicator	**Acceptable ranges**	
	Mammal/Avian bone collagen	**Fish bone collagen**
%S	0.15-0.35	0.40-0.80
C:S ratio	600±300	175±50
N:S ratio	200±100	60±20

However, in this case, the situation is more ambiguous with discussion on diagenetic alterations still ongoing (Nehlich 2015) and the concerned criteria less strictly applied. In his own more recent paper Nehlich (Nehlich et al. 2010; 2011) considers samples with C:S ratio of 296 respective 99 and N:S ratio of 92 and 29 as well preserved. Also the majority of modern fish, analyzed by Privat et al. (2007), exceed the upper limit of the recommended range, rising up to the value of 280 for C:S and 90 for N:S. As in the case of carbon and nitrogen, additional criteria are suggested to be implemented, such as the correlation of different factors and isotopic values (Bocherens et al. 2011).

Mineral fraction of the bone is much more susceptible to diagenetic processes than is collagen. Apatite consists of a number of small, unstable crystals that are predisposed to recrystallization and adsorption. Isotopic exchange or recrystallization of carbonates, via interaction with surrounding soils, microbial contamination, and other sources of degradation and disintegration, may alter the isotopic signal of the mineral part of the bone (Ambrose 1990; Nielsen-Marsh and Hedges 2000a).

Also unsuitable treatment of the sample during the lab-work may easily result in significant changes in isotopic signatures (Crowley and Wheatley 2014). For example it was proved that a too high concentration of acetic acids (used to purify bone mineral sample) promotes recrystallization (Garvie-Lok et al. 2004; Yoder and Bartelink 2010). Also the effect of different chemicals used to remove organic fraction on the carbonate content of bone is still under debate (Crowley and Wheatley 2014; Pellegrini and Snoeck 2016; Snoeck and Pellegrini 2015).

Regrettably, the detection of diagenetically altered samples is much more difficult than in the case of collagen. A number of methods have been developed to identify the effects of diagenesis on apatite samples including X-ray diffraction, Fourier transform infrared spectroscopy, histological analysis of bone microstructure, mineral content in bone, oxygen isotope analysis and radiocarbon dating of bone collagen–carbonate pairs (Ambrose 1990; Garvie-Lok 2001; Garvie-Lok et al. 2004; Nielsen-Marsh and Hedges 2000a; b; Salesse et al. 2014; Wright and Schwarcz 1996). However, being expensive, time-consuming and still not fully reliable (Zazzo et al. 2004), a number of studies do not apply any of them and are restricted to the assumption that good preservation of collagen suggests the good condition of the sample as a whole (e.g. France et al. 2014; Salesse et al. 2013). Because this study is not primarily focused on the analysis of bone apatite, we have kept this strategy as well in a small sub-sample of our apatite samples.

4 SKELETAL INDICATORS OF HEALTH AND THEIR RELATION TO DIET

4.1 Relationship between diet and health

Dietary composition is a key component of human health and survival. Here it should be stressed that diversity of diet is at least as important determinant of health as a sufficient energy intake. It has been documented many times that an unbalanced and monotonous diet increases significantly both morbidity and mortality risk. There are more than fifty essential nutrients required by the human body for growth and cell maintenance and repair. A majority of them cannot be manufactured by the body itself and must come from outside food sources (Hockett and Haws 2003; Kant and Graubard 2005; Kant et al. 1993; Lee et al. 2011).

Although the food pathways of past populations, and also the subsequent threats resulting from impaired diet, without doubt differed from those afflicting modern industrialized populations, the basic premise seems to be valid across time and space (Hockett and Haws 2003). As one example for all, a decline in health and quality of life has been documented repeatedly during the period of the introduction and subsequent intensification of maize agriculture (Kealhofer and Baker 1996; Knudson and Stojanowski 2008; Larsen 1994; 2001; Larsen and Milner 1994; Steckel and Rose 2002) which has been attributed to nutritional insufficiencies associated with a monotonous maize-based diet.

Malnutrition acts in a synergistic interaction with infectious disease. On the one hand, general weakness and reduced immune response in malnourished individuals makes them more susceptible to the effects of infectious diseases while, on the other hand, infection (especially some types such as diarrhea) may prevent the proper absorption of nutrients and minerals. This synergism between malnutrition and infection promotes each of them in several stages as the body attempts to compensate until either recovery or death (Saunders and Hoppa 1993).

Moreover, malnutrition has also an indirect effect on the health status of a population. In populations under nutritional stress, the migration rate may be increased due to the effort to gain food, which then facilitates the spread of infectious diseases. Additionally severe malnutrition may lead to a decrease of energy expenditure, lethargy and lowered capacity to produce further food (Mokyr and Ó Gráda 2002).

Due to the above mentioned synergism between malnutrition and infectious disease, it is usually not possible to tease apart the role of both in the etiology of non-specific indicators of stress in past populations (Saunders and Hoppa 1993). However, evaluation of the relationship between dietary indicators and health status markers, at the level of individuals rather than populations, may help to reveal the role of diet more thoroughly. It may also address the still open issue of osteological paradox (Wood et al. 1992). According to this theory, skeletons with more pathological lesions are not necessarily those of individuals who were less healthy than those whose skeletons are without any pathology. Better nutritional status is one of the factors which may prolong survival under the pathological condition for a longer time, extending the time necessary to develop the bone lesions.

4.2 Breast-feeding, weaning and health

It has been proved many times that the effect of diet on health and physical well-being is higher during the first years of life. During this relatively brief period, an organism has to, without doubt, face the greatest dietary change of its entire life: the process of weaning. It has been demonstrated that the timing and circumstances of the introduction of complementary food, as well as of the final cessation of breastfeeding, have great potential not only to immediately affect the growth and health of an infant or child (Kramer and Kakuma 2009; Lamberti et al. 2011; Wilson et al. 2006) but also influence its development and future health, in the long term (Demmelmair et al. 2006; Haines and Kintner 2008; McDade 2005; Palou and Pico 2009).

The optimal timing of weaning is defined by the so-called “weanling’s dilemma” (Lutter 1992): the necessity to balance out the known protective effect of exclusive breastfeeding against infectious morbidity on the one hand and the insufficiency of breast milk alone to satisfy the infant’s nutritional requirements beyond a certain age on the other hand (Fewtrell et al. 2007; Foote and Marriott 2003; Kramer and Kakuma 2009; McDade and Worthman 1998; Wilson et al. 2006).

During weaning, infants first lose the immunological protection provided by breastmilk (Newman 1995), and, second, they come into direct contact with environmental pathogens through complementary food (which may have special importance in the case of archaeological populations) (Katzenberg et al. 1996). According to actual recommendations, the optimal length of exclusive breastfeeding is at most 6 months (Fewtrell et al. 2007; Kramer and Kakuma 2009; WHO 2002). The positive effect of the continuation of partial breastfeeding during the first 2 years of life has also been demonstrated (Lamberti et al. 2011; Prentice 1991).

However, as essentially a biocultural phenomenon, infant feeding practices are highly variable and the age of weaning is adjusted to particular environmental, cultural, and economic conditions (Fildes, 1995). Feeding practices are one of the expressions of parental investment. These are substantially affected by the level of environmental risk. Parental effort is inversely associated with episodes of extreme stress such as famine and warfare. There has also been proved quadratic association with pathogen stress, with parental effort increasing as pathogen stress rises to moderate levels, but decreasing at higher levels (Quinlan 2007).

Another set of factors, affecting the decisions concerning weaning, emerges from economic or subsistence strategies. With mothers employed away from the household or exposed to a heavy workload in a tough environment the duration of breastfeeding is also negatively affected (Nitsch et al. 2011; Thorvaldsen 2008). And finally, one of the strongest influences on women’s beliefs about optimal feeding practices come from cultural background factors, including medical and religious ideas, and sexual taboos (Fildes 1995; Thorvaldsen 2008; Yovsi and Keller 2008). Due to the adaptations of breastfeeding patterns to these external factors, infant feeding practices may became unsatisfactory to the infant’s physiological needs and threaten its health, growth, and development (Fildes 1995).

4.3 Studied health indicators

4.3.1 Dental caries

Dental caries is defined as an infectious disease in which microbial activity on the tooth surface results in progressive destruction of the tooth structure. Dental plaque contains acid-producing bacteria which initiate the process by partial and local demineralization of enamel which typically progresses to substantial destruction of both the enamel and underlying dentin. Caries may be found also at the dental root as a result of the exposure of the root to cariogenic bacteria by periodontal disease (Ortner 2003; Pindborg 1970).

Before stable isotope analysis became a wide-spread and common tool, studies of caries distribution was one of the few tools accessible to bioarchaeologists to reconstruct the diet in past populations (Adler and Turner 2000; Arcini 1999; Armelagos 1966; Cucina and Tiesler 2003; Larsen et al. 1991; Lukacs 1996; Milner 1984; Powell 1985; Saunders et al. 1997; Sealy et al. 1992).

One of the big topics of these studies was the change in caries prevalence in relation to the adoption of agriculture. Often these studies have found that hunter-gatherers show a significantly lower frequency of carious lesions than do populations whose subsistence strategy was based on agriculture (Bennike 1985; Brinch and Moller-Christensen 1949; Milner 1984; Moore and Corbett 1971; 1973; 1975; Powell 1985but see Eshed et al. 2006; Temple and Larsen 2007).

In many of the studied populations, sex was shown to be an important factor in the susceptibility to caries with females often having a significantly higher frequency of carious teeth than do males (Larsen 1983; Larsen et al. 1991; Lukacs 1996; Walker and Erlandson 1986). Physiological factors (i.e., changes in female sex hormones during pregnancy) are supposed to be mainly responsible for this trend. This pattern was, however, not universally found around time and space, which suggests cultural differences in diet may also contribute to differences in caries prevalence (Larsen 1997; Lukacs 1996; 2011). Differences in caries frequencies are also often found among members of different social classes with lower class individuals being more susceptible to caries than members of the elite (Arcini 1999; Frayer 1984; Wells 1975). All these differences are usually linked with dietary content of cereal grain *vs.* milk and meat products. Cereals are supposed to be highly cariogenic due to their high content of carbohydrates (Hillson 1996).

The common pattern was also observed for the Great Moravian population where: 1) females were more often affected by caries than males; 2) individuals buried in poor graves showed significantly higher incidence of caries and 3) the socio-economically privileged population group from Mikulčice center had less caries than the rural population (Hanáková and Stloukal 1987; Stránská et al. 2008).

4.3.2 Periapical lesions

Periapical lesions develop as a secondary effect of advanced dental caries when tooth destruction from dental caries penetrates the pulp cavity and the support tissues are infected. Bone tissue reaction to infection initially involves bone destruction around the base of the tooth root. In a more advanced stage it progress to create a drain for pus through the alveolar process. Tooth exfoliation and hematogenous dissemination of the infection are additional potential secondary effects (Ortner 2003).

4.3.3 Periodontal disease (Periodontitis)

Periodontitis is a result of untreated gingivitis: an inflammation of the soft tissues that immediately surround the tooth. In periodontitis the alveolar bone is lost along with the periodontal ligament. This undermines the support structure of the tooth and finally results in tooth loss. The diagnosis of periodontal disease in dry bone samples is possible when destructive remodeling of the alveolar process is present with significant root exposure of present teeth and no evidence of abscess (Larsen 1997; Ortner 2003). Due to the continuous eruption during adulthood to adjust for occlusal wear, in archeological specimens we cannot base the diagnosis only on the root exposure but the loss of surface cortical bone and the exposure of the cancellous structure of the underlying supporting bone is key evidence for the diagnosis of periodontitis (Clarke and Hirsch 1991). The situation is more complicated in the case of tooth loss, where it can be difficult to distinguish whether the tooth exfoliation resulted from the dental caries or periodontitis.

The underlying causes of periodontal disease may be multiple and are in general unidentifiable in dry bone specimens. The main role is attributed to bacteria (many taxons). But other factors were suggested to contribute to the development of this condition including poor oral hygiene, cariogenesis, malocclusion and also diet (Larsen 1997). As in the case of dental caries, the high rate of periodontal disease and tooth loss was found in populations with a high dependence on plant carbohydrates, while foragers with a diet characterised by a higher proportion of animal protein showed a much lower incidence (Costa 1980; Frayer 1984; Larsen et al. 1995; Lukacs 1992; Owsley et al. 1987; Rose et al. 1993; Sledzik and Moore-Jansen 1991 but see Eshed et al. 2006).

4.3.4 Dental wear

Wear is caused by the grinding of teeth against one another and from contact with food, the cheeks and tongue. Though the rate of wear depends on many factors, the character of diet is clearly one of the main determinants. That is why dental wear is discussed and evaluated here, though it is not considered a pathology but a normal physiological process. It may however predispose an individual to the development of a pathological condition such as caries or pulpitis (Hillson 2005; Larsen 1997).

The severity of wear is highly influenced by the texture and consistence of food consumed as well as by its preparation techniques. Generally, the sharp decline in the severity of wear is observed in comparison of hunter-gatherers (i.e., people depending on hard-textured, often unprocessed food) with agriculturalists, consuming soft-textured foods

(Eshed et al. 2006; Lubell et al. 1994; Powell 1985; Sciulli and Carlisle 1977; Smith 1982). On the other hand, the use of grinding stones used to make flour from cereal grains may introduce a high number of abrasive elements into the diet of populations with a diet based on cereals if these are not consumed in the form of porridge (as is common in the case of maize or millet) (Larsen 1997).

4.3.5 *Cribra orbitalia* and porotic hypersostosis

Both *cribra orbitalia* and porotic hyperostosis are porotic lesions of the cranium, afflicting the orbital roof or the cranial vault and were traditionally considered to be bone response iron-deficiency anemia. The expansion of hemopoeitic tissue inside the diploic space is accounted to be the actual cause of this condition. As the diploë expands to allow for greater red blood cell production, the diploic trabeculae are reoriented to a vertical, hair-on-end pattern. Finally the outer lamina is thinned and perforated and the diploë becomes visible (Ortner 2003).

As the lesions are much more commonly found in sub-adult skeletons, they are routinely used in studies of child morbidity as non-specific indicators of stress (e.g. Bennike et al. 2005; Larsen 1997; Lewis 2010). They could be found in adults as well, though in the much lower frequencies and particularly in younger age groups (Ortner 2003). The reasons for this are still being discussed. It has been suggested that the marrow of the diploë does not produce red blood cells during adulthood at all and so the observation of *cribra* in adult crania is only the result of a slow remodeling of these bone lesions (Stuart-Macadam 1985). However, others argue that the hemopoeitic marrow between the cranial vaults and in orbits is not completely replaced by fatty marrow and retains some of its red blood cell production capabilities into adulthood (Sullivan 2005).

One of the most common causes of iron deficiency is an iron poor diet (Ortner 2003). However not only the total amount of iron in the diet is important. Certain foods, either alone or eaten in combination with other foods, may play an even more significant role in the occurrence of iron-deficiency anemia. Iron from meat sources is more easily absorbed by the body than iron from vegetal sources. In addition, some foods, such as phytates in cereals, retard the absorption of iron by the body no matter what the source (Baynes and Bothwell 1990; Danforth 1999; Gillooly et al. 1983; 1984).

However, the traditional explanation linking the genesis of *cribra* with iron deficiency anemia has been disputed (Walker et al. 2009; Wapler et al. 2004) and other potential causes such as inflammation, osteoporosis or other types of anemia were suggested to play a main role in the genesis of *cribra*. In some cases, taphonomic origin could not be excluded.

Though these alternative explanations to the traditional theory of iron-deficiency make the link between diet and the development of *cribra orbitalia* highly disputable, some suggestions of the role of the quality of diet still persist. The correlation between the high reliance on cereals and maize and the presence of *cribra orbitalia* and porotic hyperostosis is often observed in historical populations (Armelagos and Cohen 1984; Bocquet-Appel et al. 2008; El-Najjar 1976; 1982; El-Najjar et al. 1975; 1976). From the alternative explanations, megaloblastic anemia may be also linked to inadequate diet. Among other causes, it may be the result of a low consumption of vitamin B_{12} or folic acid. Vitamin B_{12} is found in liver, meat, marine fish and dairy products. For folic acid the main sources are leafy green vegetables, liver and many fruits (Baik and Russell 1999; Hawkes and Villota 1988; Sullivan 2005).

4.3.6 Endocranial lesions

"Endocranial lesions" is a term for a reactive new bone formation on the endocranial surface of the skull vault of subadults. They could be of multifactorial origin and are therefore included in a group of non-specific stress indicators. They are most commonly found at the occipital bone (outlining the cruciate eminence) but may be also recorded on the parietal and frontal bone. Layers of new bone appear on the original cortical surface, especially around meningeal vessels, in the form of isolated plaques (so- called 'hair-on-end' extensions of the diploë) or as vascular impressions extending into the inner lamina of the cranial vault (Lewis 2004; 2007). Due to the high incidence and special character of lesions observed in the youngest infants Lewis (2004) suggests that, in young infants, this feature is probably non-pathological in origin and results from the rapid growth in that area.

4.3.7 Growth and stature

The analysis of growth pattern as well as of attained adult stature is often used to provide insight into the nutrition of a population. A developing human organism uses the acquired energy in the first place for the maintenance of vital functions, reparation processes and work-expenditure. Only after all these needs are met could energy be invested into growth. Growth retardation is one of the first responses of an organism to nutritional deficiency. Individuals with a poor diet are thus less likely to attain their genetic stature potential (Allen 1994; Bogin 1999; Carson 2008; Lejarraga 2002; Norgan et al. 2002; Rivera et al. 2003).

The impact of diet is extremely important during the first years of life. It has been proved that growth during the early childhood years is more sensitive to nutritional disruption than during the adolescent growth spurt (Bogin 1999; Gørgens et al. 2012).

In historical populations, the relationship between the access to animal protein and the attained stature was suggested repeatedly (Baten and Murray 2000; Koepke 2010; Koepke and Baten 2008). The important source of animal protein, which was often suggested to be responsible for observed differences in stature, is milk. Milk could not be transported for longer distances, so was consumed mainly in the area of its production (i.e., in rural areas). On the other hand, in the urban agglomerations, only higher classes could afford protein-rich food based mainly on meat. On a global scale, proximity to milk production was an important determinant of attained stature until the 1940s, since after that its importance sharply declined due to the better food preservation methods (Blum and Baten 2010). However, in sub-Saharan Africa, this was a significant stature determinant until as late as the second half of the 20th century (Moradi and Baten 2005).

In the Great Moravian population a study of stature was performed, focusing on the population of Mikulčice (divided into the “Castle” and “Suburb” sub-groups) and its hinterland, represented by Josefov and Prušánky. According to this study, Great Moravian people were of relatively tall stature when compared to other historical populations with an average stature of 170cm in males and 161cm in females. No significant differences were found among distinct population sub-groups (Dobisikova et al. 2008). This suggests good living conditions enabling the attainment of the genetic potential for stature in at least a majority of the population.

5 MATERIAL

All the sites included in this study (Table 3) are located at the presumed core of the Great Moravian state formation in the south-eastern part of today's Czech Republic (Fig. 2). They may be divided into three main subgroups according to the socio-economic and temporal stratification: the Great Moravian centers; the Great Moravian hinterland, representing (with some reservations discussed below) the rural population; and finally the late Hillfort sample, representing the post-Great Moravian phase of the occupancy.

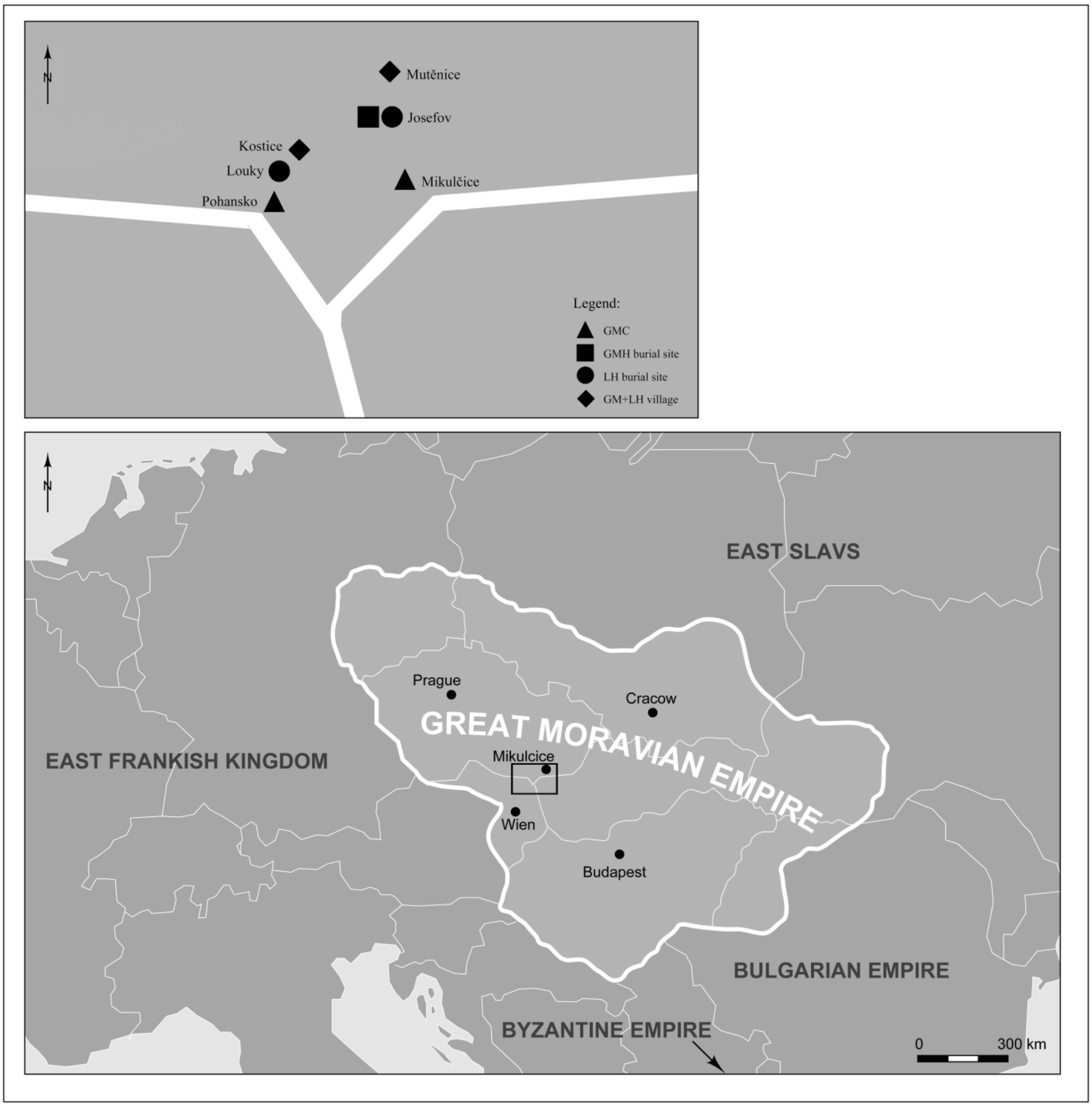


Fig. 2. Location of studied sites, modified illustration according to Havelková et al. (2010) and Kaupová et al. (2014**).**

TABLE 3. Description of studied sample

Site	Period	Context	Adults[a]	Sub-adults[a]	Animals[b]
Mikulčice	Great Moravian	Center	70/70	23/144	38: C (5), S/G (6), P (5), D (3), Fo (3), H (2), WH (4), WB (1), B (2), Fi (6), Be (1)
Pohansko	Great Moravian (late)	Center	56/0	0/0	8: C (1), S/G (1), P (1), Fo(1), WH (1), WB (1), Fi (1), Be (1)
Josefov I	Great Moravian	Hinterland	32/32	18/47	3: P (1), Fo(2)
Mutěnice	Great Moravian	Hinterland	0/0	0/0	15: C (4), S/G (4), P (4), Fo (1), H (2)
Prušánky I	Great Moravian	Hinterland	0/0	0/111	0
Josefov II	late Hillfort	Hinterland	21/0	0/0	0
Louky	late Hillfort	?	10/0	0/0	0
Kostice	late Hillfort	?	0/0	0/0	10: C (3), S/G (3), P (3), Fo (1)

[a] No. of individuals sampled for isotopic analysis/No. of individuals under the osteological examination.

[b]Total No. of samples: No. of samples of particular species (C = cattle; S/G = sheep/goat; P = pig; D = dog; Fo = fowl; H = Horse; WH = wild herbivores; WB = wild boar; B = bear; Fi = fish; Be = beaver).

5.1 The Great Moravian centers (GMC)

The character of the Great Moravian centers as well as their crucial role in the functioning of Great Moravian society was clearly defined in Chapter 2. From the archaeological point of view, it is important that these proto-urban agglomerations were subjected to long-term and systemic archaeological research of an unprecedented extent for several decades. Another advantage of both sites included into this study lies in their relative preservation with both almost undamaged by later city developments (Dostál 1975; Macháček et al. 2014; Poláček 2008b; Poulík 1975).

5.1.1 Mikulčice

The agglomeration of the settlement complex in Mikulčice is believed to be one of the prominent power centers of the Great Moravian Empire and an important center of Christianity in this territory as well as, at least temporarily, the residence of the ruling Mojmír dynasty. It had a character somewhat between a military fortress and an early urban formation with a high concentration of ecclesiastic buildings. In each case it attained a degree of urbanization unprecedented in this area (Měřínský 2006; Poláček 2008b; Poulík 1970; Třeštík 2001). The settlement complex consisted of the fortified core (including *acropolis* or “castle” and the bailey), and suburbs (Fig. 3) which gradually grew around the fortified center (Poláček 2008b; Poláček and Marek 1995). The occupied area of agglomeration is supposed to have been between 30-50ha. However, especially in the sub-castle area, many parts (especially marshes and water surfaces) remained unoccupied, or were of only limited use. The number of inhabitants is estimated to be between 1000-2000. While discussion still continues, the violent destruction of the agglomeration with the subsequent disruption of residential continuity is suggested to have happened (Hladík 2014; Hladík and Mazuch 2010; Poláček 2008a; b; Poulík 1975; Stloukal and Vyhnánek 1976).

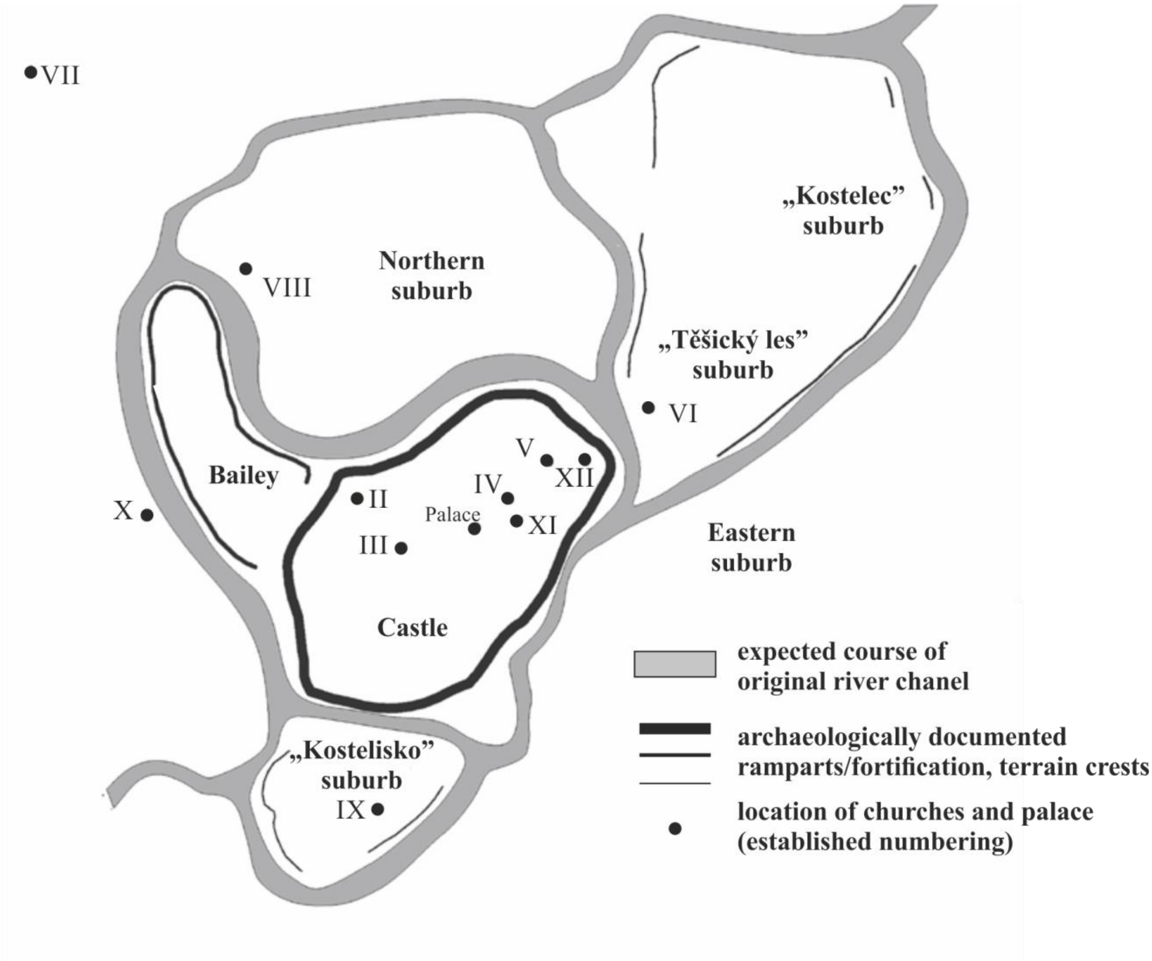


Fig. 3. Great Moravian settlement agglomeration of Mikulčice (modified according to Poláček 2008b).

Since the 1950s extensive archaeological research has been going on at Mikulčice. Until now more than 2500 graves have been uncovered, both in suburbs and at the *acropolis*, dated to the 9th and the first third of the 10th century. The findings of presumably dynastic graves in the interior of the main churches as well as the concentration of richly equipped graves support the idea of the presence of the true elites of Great Moravian society (Poláček 2008b; Poláček and Marek 1995).

In this study, attention was paid to the population buried in the area of the castle, which is thought to be a residential area of the privileged class. A sub-sample of 70 adult individuals was sampled for stable isotope analysis. These 70 individuals were selected from among the adults for whom sex and age-at-death could be estimated and chosen to include individuals with a different number and quality of grave goods. All of them were buried around the so-called 2nd and 3rd church. One of the studied individuals (MIKH46) comes from the interior of the so-called 2nd church where he was buried with rich grave goods including a sword. Both these characteristics suggest the outstanding status of this individual. From sub-adults, 23 individuals were selected in such a way that the age classes and individuals with a different quality of grave goods were distributed as equally as possible in the sample. Sub-adults came from all the cemeteries within the *acropolis*.

From the same area of the acropolis, a sample of 38 animals was analyzed for carbon and nitrogen, including 6 remains of fish (carp, dace, pike and three undetermined species). In a sub-sample of 17 samples (including 6 freshwater fish) with sufficient collagen yields, sulphur isotopic values were also measured.

Osteological examination was effectuated at the same sample of 70 adults. In sub-adults another strategy was chosen: all the individuals aged 0-6 years and buried in the castle area were examined, which comprises 144 individuals.

5.1.1.1 Isotopic analysis of diet in Mikulčice

Mikulčice was the only one of the studied sites where, until now; isotopic analyses of diet has been performed. They were, however, of a limited sample size and focused only at the Mikulčice – Kostelisko suburb. The first one was performed by Smrčka et al. (2008) on 10 individuals. Through this small sample size, the authors have suggested socio-economically motivated differences in both carbon and nitrogen isotopic values, with people from rich graves consuming more animal protein and millet. The real values (-18.9±0.5 for $\delta^{13}C$ and 10.7±1.2 for $\delta^{15}N$) are however difficult to compare with our data because the method (Stafford et al. 1988) used to extract collagen differs at all steps from that applied to our samples. No animal samples were analyzed in this study.

A more recent study by Halffman and Velemínský (2015) was also focused on the population of the Kostelisko suburb and presented the results on 33 human and 18 faunal collagen samples. Though also limited in sample size, this study provided the first plausible description of the Great Moravian diet which appeared to be based on terrestrial resources, with millet being an important dietary resource. The intra-population variability is however beyond the scope of this brief survey. The collagen extraction method used in this study comes from the Longin (1971) method and, though it differs in some details from our methodology, we consider the data reliable enough for comparison with our results. Moreover, data from animal bones may be used as a control for potential differences between both studies.

5.1.2 Pohansko

The Pohansko site is located approximately 2km from the town of Břeclav near the Czech-Austrian border. Though the beginnings of early medieval (Slavic) occupation of Pohansko date back to the 6th century AD, until the 8th century only a small agricultural village (accompanied by a burial site with 55 cremations) is documented (Dostál 1985). In the 9th century, this agricultural settlement was replaced by the agglomeration with a fortified core and adjacent suburbs. Inside the fortified core the research recorded structure interpreted as a magnate's court with a stone built church and corresponding cemetery as well as an artisanal area with graves scattered within the settlement (Dostál 1975; Macháček 2005; Macháček et al. 2014).

Pohansko is supposed to have been dependent on the principal center of Mikulčice. It is presumed to have been built up by the ruling dynasty at a spot chosen for its strategic position at the junction of the Morava and Dyje rivers. Due to this location, Pohansko had an important function in the defense of Great Moravia as well as being a center of trade and crafts (Macháček 2005; Macháček et al. 2007). As in the case of Mikulčice, at least a partial dependency on the agricultural production (especially of cereals) of villages located outside the flood plain is supposed (Macháček 2005). The greatest extension of the Pohansko agglomeration is dated to the last quarter of the 9th century. The final reduced occupation ended in the first half of the 10th century after which the site was definitely abandoned (Macháček 2005).

The site has been continuously explored since 1958. Until 2005 about 850 graves in several locations (both inside and outside the fortified core) were discovered but the church in the magnate's court remained the only documented religious building (Macháček 2005). In 2006 archaeological research in the north-east suburb revealed the remains of previously unknown early medieval church architecture – a rotunda surrounded by a cemetery (Fig. 4) where 152 individuals were buried (Macháček et al. 2014).

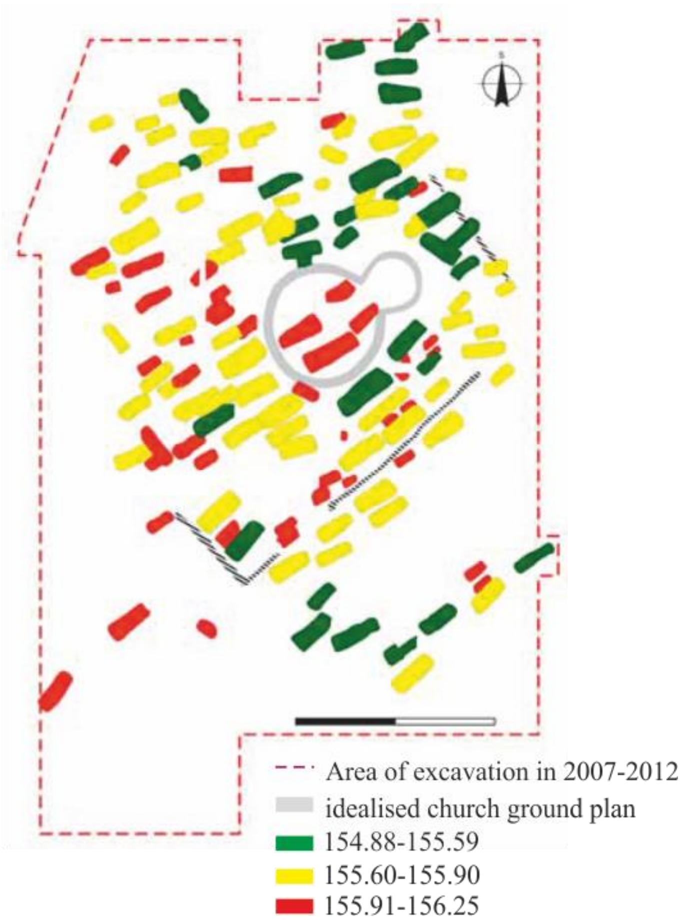


Fig. 4. Pohansko – north-east suburb: rotunda with the adjacent cemetery (modified according to Macháček et al. 2014). Altitude of the bases of the graves is marked by colors.

The construction of the rotunda can be dated to the second half of the 9th century, lasting into the first decades of the 10th century (Macháček et al. 2014). Two men, and three children aged between eighteen months and twelve years, were buried beneath the floor of the church. This is rather exceptional in the Great Moravian context where the graves in the interior are documented almost exclusively only in the most significant churches linked to the residence of the elite classes, such as the three-nave basilica in Mikulčice or the cathedral complex in Sady near Uherské Hradiště. The only analogy to this situation known up to now is the 12th church in Mikulčice which has 5 graves in the interior (Kavánová 2001). Not only the presence of graves in the interior, but also a simple building technology (a wooden load-bearing structure) and the absence of rich grave goods are common to these two structures. A similar situation – though without the interior graves – was also described in the case of the 7th church in Mikulčice, located at the periphery of the agglomeration (Kouřil 2010). This leads to the hypothesis that these buildings reflect some degree of pauperization and the fracturing of the strict societal regulations during the decline of the Great Moravian period (Macháček et al. 2014; Poláček 2008b), when the emancipated nobility of a lower rank started to build up their own sanctuaries at the peripheries of declining centers.

Grave No. 153/POHH29 (Male, 50+ years) was, due to its prestigious position on the main axis of the church, with some uncertainty assigned to the probable founder of the church. Though he is supposed to have been a member of the Great Moravian nobility, his exact position in the socio-economic hierarchy is not known. The other interior graves are supposed to be those of members of his family (although we cannot exclude the presence of the grave of a local priest), while outside servants and other people in a dependent status are supposed to be buried (Macháček et al. 2014).

Since 2012, the corresponding settlement area has been systematically excavated at the north-east suburb. During these excavations, a structure interpreted as a residential court of nobility, who would have instigated the construction of the adjacent church, was exposed (Dresler et al. 2014; Macháček, personal communication).

For this study, all the adult individuals (N=56) buried in and around the rotunda were sampled while the excavation of the corresponding settlement area provided animal bones, from which a sub-sample of 10 was chosen for the analyses including one fish of undetermined species. Four of these samples (including the only analyzed fish sample) provided enough collagen to also measure sulphur isotopic values. Sub-adults were not sampled for the stable isotope analyses. Also skeletal remains were not accessible for palaeopathological examination at the time of this study. Demographic data (sex and age-at death) were provided by Vladimír Sládek and his co-workers (Sládek et al. unpublished data).

5.2 The Great Moravian hinterland (GMH)

In the traditional view, this group should represent the rural part of the Great Moravian population whose main role lay in supplying growing neighboring centers with agricultural products and other raw materials. But, for several reasons, our knowledge concerning the true nature of the occupation and socio-economic structure of this population group is limited. Firstly, with a few exceptions (Dreslerová et al. 2013; Klanica

2008), our current image of the hinterland is based mainly on burial sites, with a lack of information from corresponding settlements. Moreover, the often small extent of excavations and the low state of preservation of skeletal material recovered from "hinterland" burial sites reduces its predicative power (Poláček 2008b; Stránská et al. 2002).

Despite the unsatisfactory state of research, there are some indications, such as the presence of warrior graves in the "rural" burial grounds or the untypical demographic structure of the skeletal samples recovered from these graveyards, which suggest a higher social complexity and the varying occupations of this population group (Poláček 2008a; b; Poulík 1975; Stloukal and Vyhnánek 1976).

5.2.1 Josefov I and Mutěnice

This site is situated in the valley of the Prušánka stream, 7km from Mikulčice, i.e., within the area which is estimated as being the agricultural hinterland of that center (Poláček, 2008a; b). Josefov is considered to be an example of a "poorer" rural Great Moravian burial site. During the excavation in 1957–1962, a total of 171 graves with the skeletal remains of 178 individuals were uncovered (Fig. 5). It is supposed that the whole area of the Great Moravian burial site was uncovered. A majority of the graves (74%) contained grave goods, typically a simple inventory (especially ceramics) with less distinctive evidence of social stratification (Klíma 2007; Poláček 2008b). The "warrior" graves were present though more rare (5.6%) than in most of the other Great Moravian burial sites (Hanáková and Stloukal 1966; Poláček 2008b; Stránská et al. 2002; Šráčková 1962).

All the adults with an estimated sex (N=32) were sampled for this study. Due to the absence of the corresponding settlement, only three pieces of animal bones were recovered at this site and thus were accessible for analysis. So in order to get some feel of the isotopic background of areas outside the flood plain in more detail, 15 animals were chosen for analysis from the contemporaneous village of Mutěnice (Klanica 2008). For sub-adults the samples were taken from all the individuals whose state of preservation enabled sampling, resulting in a total of 18 individuals.

Osteological examination was performed on the sample of adults as chosen for the stable isotope analysis, and on all the sub-adults (N=47) of the appropriate age (0-6 years). Since the number of sub-adults was too low for the statistical evaluation, the sample of sub-adults was enlarged by adding individuals from the nearby site of Prušánky I.

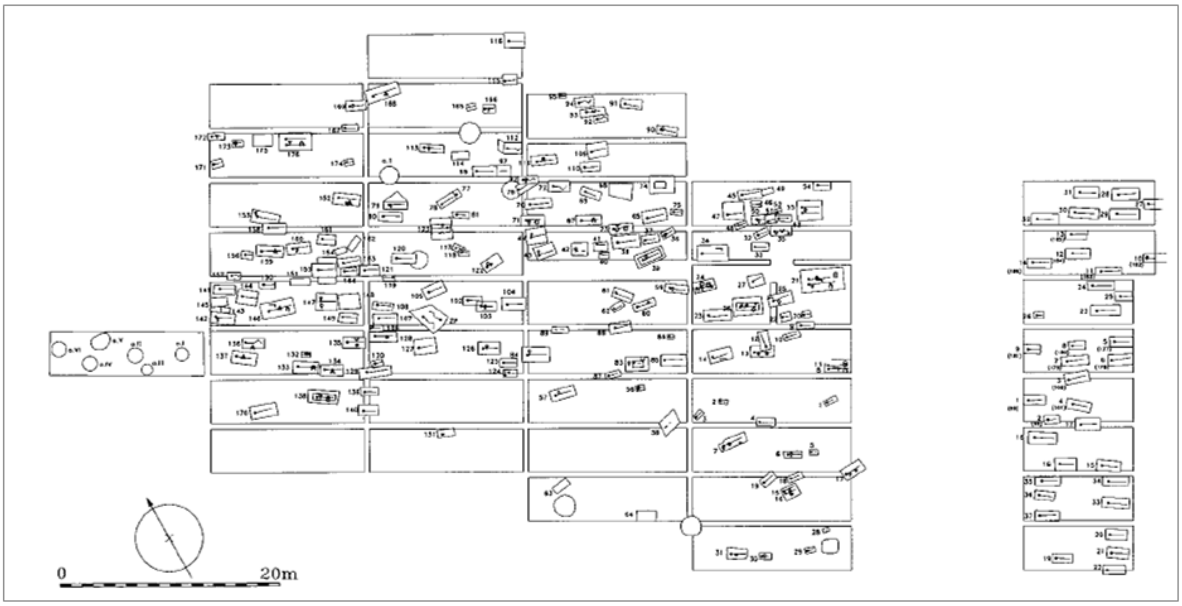


Fig. 5. Josefov: Great Moravian burial site (Josefov I) at left, partially explored late Hillfort burial site (Josefov II) at right (modified according to Klíma 2007).

5.2.2 Prušánky I

The Prušánky site, located 9.5km from Mikulčice, consists in fact of two temporary overlapping burial sites. Both of them were almost completely excavated during the 1970s and 1980s. The reason for the existence of a pair of burial sites in close proximity to each other still remains an unanswered question. Both sites differ substantially in the quality of grave goods with Prušánky I representing a “poorer” burial site with approximately 70% of the graves containing grave goods, most commonly ceramics. The proportion of “warrior” graves was as low as 2.3% (7 graves). At Prušánky II, in contrast, the proportion of graves with findings is lower in comparison with the first Prušánky burial site (about 50 %), but the percentage of “warrior” graves and graves with rich grave goods is higher, which suggest differences in the socio-economic structure of both samples (Klanica 2006).

Due to the Prušánky site being included in the study in order to increase the hinterland sub-adult sample for osteological examination, only Prušánky I (Fig. 6) was analyzed because, according to the grave goods, the social stratification of the buried community seems to be similar - though slightly higher - as in the case of Josefov (Klanica 2006). A total of 111 sub-adult individuals were subjected to anthropological analysis.

Neither stable isotope analysis nor osteological evaluation of adults was performed on the sample from Prušánky.

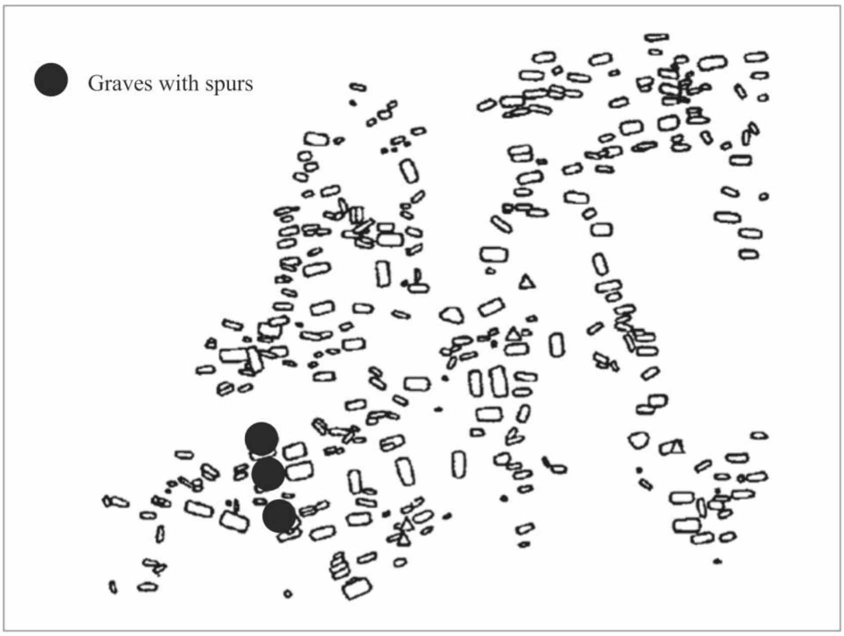


Fig. 6. Prušánky I burial site (modified according to Klanica 2006).

5.3 The late Hillfort sample

A smaller sample consisting of two late Hillfort sites was included in the study in order to observe potential diachronic change in dietary practices (especially in the consumption of millet). Regrettably, late Hillfort material comes from only partially recovered burial sites, either because of the destruction of a majority of shallow graves by ploughing (Louky) or due to the lack of interest during excavations in the 1970^{s} (Josefov) where attention was focused on the Great Moravian phase of the burial site (Dresler 2013; Klíma 2007).

5.3.1 Louky od Břeclavska and Kostice

In 2011-2012, a small cemetery was found in the field between the towns of Břeclav and Lanžhot, where a total of 11 graves were excavated (Fig. 7). Based on the inventory (S-shaped temple rings and especially coins) the cemetery was dated to the 11th century (the late Hillfort period). The cemetery is located outside the floodplain, in an elevated position on the left bank terrace of the Dyje river, about 300m from the contemporary settlement of Kostice – Zadní Hrúd from which animal bones (N=10) were sampled (Dresler 2013; Macháček et al. 2013).

The settlement of Kostice had probably played its role as part of the agricultural hinterland of the nearby center of Pohansko in the Great Moravian period while in the 11th century it gave rise to a new sub-center of crafts and a market (Macháček et al. 2013). Although we cannot be sure that the studied burial site is directly linked to the nearby settlement, it is highly probable (Macháček and Dresler, personal communication).

All the adults (N=10) were sampled for this study Neither osteological analysis nor isotopic analysis of sub-adults were performed on the skeletal material from Louky. Demographic data (sex and age-at death) were provided by Vladimír Sládek and his co-workers (Sládek et al. unpublished data).

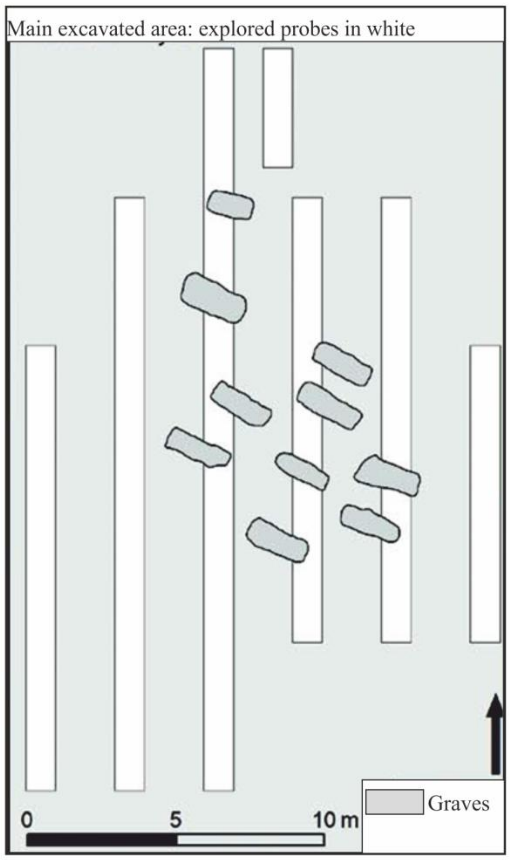


Fig. 7. Louky od Břeclavska burial site (modified according to Dresler 2013). Grave No. 9 was found isolated outside the main excavated area.

5.3.2 Josefov II

Together with the Great Moravian burial site, a much smaller group of 33 newer graves was discovered in Josefov. Unlike the Great Moravian burial site, which was uncovered as a whole, only a smaller section of the late Hillfort phase (Fig. 5) is presumed to have been explored (Poláček 2008b). The organization of the graves in regular rows, as well as their inventory, dates this graveyard to the 11th century (Hanáková and Stloukal 1966; Klíma 2007). Regrettably, little attention has been paid to this newer phase of the graveyard in archaeological records or in anthropological studies sites (Hanáková and Stloukal 1966; Stránská et al. 2002; Šráčková 1962). Therefore, together with the absence of a corresponding settlement, there is no clue to the supposed socio-economic status of the buried individuals.

All the adults (N=21) were sampled for isotopic analysis. Neither isotopic analysis of sub-adults nor osteological examination was carried out at this site.

6 METHODS

6.1 Sex and age estimation

Sex was identified on the basis of the morphometrical evaluation of the pelvic bone (Murail et al. 2005). This method was chosen because it ensures a high reliability of the sexual diagnosis (95% or more), even in cases of an only partially preserved hip bone, using a random combination of at least 4 measurements out of a total of 10. In the case of the absence of a hip bone, the skull was used according to the principle of primary and secondary sex diagnosis. Based on the metrical evaluation of skeletons, which were sexed previously using the hip bone (primary sex diagnosis), discriminant function analysis was performed using 12 linear cranial variables. Resulting equations for the secondary sex diagnosis, working with a combination of 4 to 5 measurements, showed the accuracy between 80-86% (Brůžek and Velemínský 2008).

The age-at-death estimation of adults was based on the assessment of skeletal maturation and morphological changes of the pubic symphysis and auricular surface (Ferembach et al. 1980; Schmitt 2005; 2008). Due to the sample size, for further analysis individuals were divided in two groups: “younger” (20–35 years old) and “older” (>35 years old).

For sub-adults, age-at-death estimates were obtained using primarily the dental age, concretely the method developed by Liversidge (1998). This method was chosen because it can be applied to loose teeth without the necessity of creating radiograms, which were not available for this study. Beside this, it was developed on the pre-industrial population sample from Spitalfields, so it is supposed that it reflects the growth and development scheme of a historical population more closely than methods developed as standards for modern populations. It is based simply on the linear measurement of tooth length of developing teeth. Based on these measurements, regression equations were created for each deciduous maxillary and mandibular tooth type as well as for permanent maxillary and mandibular incisors, canines and the first permanent molar. This method can be applied to individuals younger than 5.4 years. Therefore, in several cases of the oldest individuals of the studied cohort aged between 5 and 6 years, this method was not applicable. Then the standards published by Moorrees et al. (1963) tabulated by Smith (1991) were used. Individuals without recovered teeth, whose age could be estimated using growth and skeletal maturity (Scheuer and Black 2000; Stloukal and Hanakova

1978) were classified as 0.0–6.0 without further specification for the purposes of palaeopathological examination.

6.2 Sampling strategy and sample treatment for isotopic analysis

In adults, a chunk of bone of approximately 500mg was cut from each individual, using preferentially ribs or the tubular bones of hand or foot. To describe weaning strategies in the Great Moravian population, both bones and teeth were sampled for stable isotope analysis. At least 50mg of tooth dentin was sampled from the tip of the developing dental root at stage $R_{1/4}$ -$Ap_{1/2}$, after Smith (1991). The samples were taken from different tooth types in regard to the age-at-death. Where possible, the first or second deciduous molar was sampled. From the youngest individuals with insufficiently developed roots of molars, canines or incisors were used. In some of these cases, two teeth had to be sampled to obtain a sufficient amount of dentin. Additionally, at least 80mg of mandibular bone from each individual was sampled.

All the samples were taken using a manual micro-drill. In the case of bone samples, all the spongious bone was removed and the surface of bone chunks was cleaned mechanically using the appropriate grinding adapter of a micro-drill. The next pre-processing step included further cleaning with the help of an ultrasonic bath with demineralized water. Samples were then dried for 24 hours in an oven at 40°C.

Dry samples for collagen extraction were ground to particles of around 0.7mm in size using a mortar and pestle. In the case of bones samples which were too difficult to crush manually, a vibratory micro-mill was used. In a sub-sample for an apatite preparation the remaining bone was ground to a fine powder (<0.25 mm).

6.3 Collagen extraction method

The preparation of collagen samples commenced in November 2011 in the biochemical lab of Laboratoire Méditerranée de Préhistoire Europe Afrique, Aix Marseille University, Aix-en-Provence, France. From autumn 2014, samples were prepared in the lab of the Department of Anthropology, National Museum, Prague, Czech Republic. Here mainly the samples from the late Hillfort sample as well as animal samples from Mutěnice and Pohansko have been analyzed. The same extraction method: Longin (1971) modified by Bocherens (1992) was used in both institutions and the equipment and material used in both the laboratories were comparable.

6.3.1 Demineralization

In case of adults approximately 200mg of ground bone was placed in 50ml beakers. 40ml of 1M HCl was introduced to the beakers and those were placed on a magnetic stirrer for 20 minutes at room temperature. This process dissolves and removes the mineral component of bone. After that samples were filtered using glass microfiber filters (1.6µm retention) and flushed with distilled, demineralized water. After rinsing and washing the original beakers, samples were returned to the beakers.

In case of sub-adults, the sample weight was lower: 80-150mg for bone and 50-100mg for the tooth dentin. Subsequently, only 30ml of HCl was added.

6.3.2 Purification (Removal of organic contaminants)

40ml (30ml in the case of sub-adults) of 0.125M NaOH were added to beakers, and left overnight at room temperature. This step removes secondarily deposited organic contaminants (such as fungi and bacteria) and lipids (Ambrose 1990). After 20 hours, the samples were again filtered and rinsed with distilled demineralized water.

6.3.3 Solubilization of collagen particles

At the next step, the samples were transferred into 15ml glass tubes, which were then filled with 0.01M HCl. These tubes were placed into the oven and left for 17 hours at 100°C. During this time collagen particles were dissolved. On the next day, the slightly cooled samples were again filtered using 9ml Ezee filter separators. The solutions were placed into the pre-weight 20ml glass vials and frozen.

6.3.4 Freeze-drying and final sample treatment

After at least 24 hours in the freezer, the samples were taken to be lyophilized at -110°C for 48 hours. The dry samples were than weighed and the collagen content (%coll) of the initial bone powder was calculated according to the following equation:

$$\%coll = \frac{Wt_{sample} - Wt_{vial}}{Wt_{powder}}$$

Equation 2

where Wt_{sample} is the weight of the glass vial with the freeze dried collagen inside, Wt_{vial} is the pre-recorded weight of the vial before introducing the dissolved collagen sample, and Wt_{powder} is the initial weight of the ground bone sample. As discussed in Chapter 3, collagen content in bone is one of the indicators of bone preservation and collagen quality in stable isotope studies. At this stage, the samples with the sufficient collagen yield were packed and sent for stable isotope ratio analysis.

6.3.5 Stable isotope ratio analysis

Elemental analyses were performed on a Europa Scientific EA elemental analyzer connected to a Europa Scientific 20-20 IRMS for the carbon and nitrogen isotope analysis at Iso-Analytical Limited, Crewe (UK). The uncertainty of isotopic measurements calculated on different standard replicates (IA-R042, IA-R045, IA-R046 and IA-R05, IAR06) was less than 0.2‰ for both nitrogen and carbon. 20% of the samples were weighed and analyzed in duplicate in order to assess intra-sample variability and instrumental precision of the elemental analyzer and mass spectrometer.

6.4 Apatite preparation method

Apatite was extracted according to Garvie-Lok et al. (2004) as modified by Salesse et al. (2013). Approximately 18-22mg of bone powder were placed into 2ml Eppendorf tubes. To remove the organic fraction of bone, bone powder was soaked for 24 hours in 2-3% NaOCl solution. Deproteinated powders were centrifuged and rinsed five times using demineralized water.

After that 0.1M of acetic acid was added into the tubes for one hour in order to remove diagenetic carbonates. Again samples were centrifuged and rinsed five times in demineralized water. After rinsing, samples were dried overnight in the oven at 80°C. Elemental analyses were performed in the same laboratory (Iso-Analytical Ltd.) as those of collagen.

6.5 Osteological analysis

All dental pathologies (and dental wear as well) were recorded in adults only. We have evaluated the incidence of caries and intra-vital tooth loss in the dentition of adult males and females. Concerning caries lesions, we took into consideration only clear cavities. Though initial stages of caries are indicated by microscopically white or brown blemishes below the enamel surface, these were not taken into account because they are too difficult to evaluate in an archaeological context, where often discoloration of a different origin occurs. For the statistical analysis, I considered two characteristics:

1) Caries presence/absence, i.e., all individuals with at least one carious tooth or ante mortem loss were indicated as positive,

2) Index of intensity of caries (ICE) expressed as:

$$ICE = \frac{No.\,of\ carious\ teeth}{No.\,of\ preserved\ teeth} * 100 + \frac{No.\,of\ healed\ alveoli}{No.\,of\ preserved\ alveoli} * 100$$

Equation 3

This index (Stloukal and Vyhnánek 1976) thus represents the sum of the percentage values of the incidence of caries and intra-vital losses. Though ante-mortem tooth loss does not necessarily result from dental caries, it is usually impossible to recognize teeth lost e.g. as a result of accident in the archaeological context (Stránská et al. 2008).

It should be also mentioned here, that the ICE value may be significantly influenced by the preservation of the skeletal material, more precisely by the preservation of individual tooth types. In the case of the absence or poor preservation of the front teeth (which are much less affected by caries in comparison to molars), the ICE value is artificially increased. However, in our sample, all types of teeth were represented uniformly.

The presence or absence of periodontal disease and periapical lesions was inspected visually. However in the case of periapical lesions only the most severe cases, where the lytic lesion penetrated the external cortex of the jaw, could be observed in this way.

Dental wear was observed only macroscopically. The scoring technique by Scott (1979) was applied to first and second permanent molars. Third molars were not included in this study because their eruption times as well as occlusion varies significantly between individuals. Moreover, their retention or agenesis is also common (Ortner 2003). In this technique each molar is visually divided into four sections and each section scored on a 1-10 scale. The score for the whole tooth is the sum of the quadrant scores and ranges from 4-40. For the statistical evaluation, the mean value of dental wear score for all the preserved teeth was used.

The presence of *cribra orbitalia* and porotic hyperostosis were noted in both children and adults according to the method by Nathan and Haas (1966). Since the lesions are usually symmetrical, I have considered an individual to be well-enough preserved for analysis if at least one orbital roof and respectively one parietal bone was well preserved. According to Nathan and Haas (1966), three stages may be observed: A: porotic type with scattered fine perforations; B: cribrotic type, in which perforations are more numerous and tend to fuse; and finally C: trabelular type with bigger irregular holes, often radially organized. In the statistical analyses, I have considered the *cribra* lesions only as present or absent. According to some researchers, type "A" are considered too mild to represent serious health problems (Bennike et al. 2005; Lewis 2013). So in sub-adults, we have repeated the statistical analysis by considering only cases graded as "B" and "C" as positive. In adults, however, this was not possible, because more severe lesions were not observed at all.

In sub-adults, the endocranial lesions were evaluated as present or absent according to the criteria proposed by Lewis (2004). The type of lesion was not considered. Since Lewis suggests rapid growth to be a complicating factor in the youngest individuals, the statistical tests were repeated removing all individuals up to 1 year of age from the analysis.

To evaluate the attained adult stature, the maximum femur length (M1 according to Martin, cited in Bräuer 1988) was measured. Preferentially, the left femur was used. In case of absence or a low state of preservation for a given skeleton, I substitute the measurement for the right femur. As there is error involved in any stature estimation from long bone length, I use only femur length in my comparison of stature differences. In sub-adult samples diaphyseal length, antero-posterior (AP) and medio-lateral (ML) diameter at the midshaft of femur, tibia and humerus were measured to monitor both endochondral and appositional growth (Mays et al. 2009).

6.6 Statistical analysis

To compare isotopic values among biologically and socio-economically defined sub-samples, we used at the first place the independent samples *t-test* and *ANOVA*. Where the data did not meet a normal distribution (which is a common feature of isotopic data) or homogeneity of variances, the *Mann-Whitney test / Welch two sample t- test* and *Kruskal-Wallis test* were applied.

To establish a potential difference in weaning strategies between the two sub-groups of the Great Moravian population, simple and multiple logistic regressions, and subsequently the *Wald test*, were performed to evaluate the effect of age (median age) and type of residency on the presence of breastfed/weaned status. The consideration of age in multiple regression permits the adjustment of the results for this variable. Moreover, the interaction between age and type of residency has been tested to determine if the potential age-related trends are similarly apparent in both sub-samples.

For the osteological data of the adult sample, at first the data was checked for the potential relationship between skeletal health markers and demographic data (sex and age-at-death). In the case of categorical data (*cribra orbitalia*, periodontal disease, periapical lesions) the *Fisher exact test* was used while for the continuous data (ICE, dental wear score, femur length) the *t-test* or its non-parametric alternatives - *Mann-Whitney* or the *Kruskal-Wallis test* - were applied. All the further analyses were effectuated for males and females separately. The effect of the age factor was taken into account when the choice of actual statistical analysis was in issue. For the categorical data with the significant impact of the age at death, logistic regression was used to discover the potential relationship between dietary indicators and skeletal health markers. When the presence of a lesion appeared to be independent at the age at death, the *Mann-Whitney test* was applied. In the case of continuous data, *Kendall's tau-b* correlation was used, where the age-at-death factor was insignificant. When the contrary was true, general linear models (GLM) were applied to the data.

For the sub-adult sample, regarding the presence of non-specific stress indicators, again logistic regression taking into account the median age was applied. To evaluate the influence of the type of residency on the growth in different skeletal dimensions the method developed by Mays et al. (2009) was applied: a polynomial regression for each of the dependent variables (bone length, AP or ML) on dental age was fitted. This procedure enabled investigation of the differences in bone dimensions between center and hinterland individuals, controlling for the effect of dental age by carrying out the analysis of the regressions' standardized residuals. Since these did not meet a normal distribution, the center *vs.* hinterland differences were verified by a non-parametric test, the *Mann-Whitney test* for independent data.

The analyses were performed by the Statistica v7.0, R v12.1, and the SAS/STAT® software v12.1.

7 RESULTS AND DISCUSSION

Complete datasets of isotopic data are presented in Appendix.

7.1 Isotopic data of fauna

7.1.1 Data quality

Visually, the state of preservation of animal bones appeared to be highly variable, ranging from dense samples with a compact surface to the dry, chalky, porous ones. This pattern was common to bones from all the studied sites regardless of the time period or natural context. All the samples met the criteria for good collagen preservation (DeNiro 1985; van Klinken 1999). Moreover, no statistically significant correlation was observed between collagen quality indicators and isotopic data (Table 4, Fig. 8). But due to a huge variability of isotopic data related to the differences in subsistence, habitats or metabolism of different animal species, the power of this analysis is limited. We thus repeated the analysis only for the group of “domesticated herbivores” (i.e., sheep/goats and cattle) in order to diminish the effect of these factors. Again there was no sign of potential sample contamination or diagenesis.

TABLE 4. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{13}C$, $\delta^{15}N$) and collagen preservation criteria in animal sample

		Yield (%)	Carbon Content	Nitrogen Content	C:N
All animals	**δ^{13}C**	0.197	0.343	0.473	0.127
	δ^{15}N	0.438	0.772	0.472	0.098
Domesticated herbivores	**δ^{13}C**	0.478	0.331	0.295	0.147
	δ^{15}N	0.568	0.292	0.250	0.813

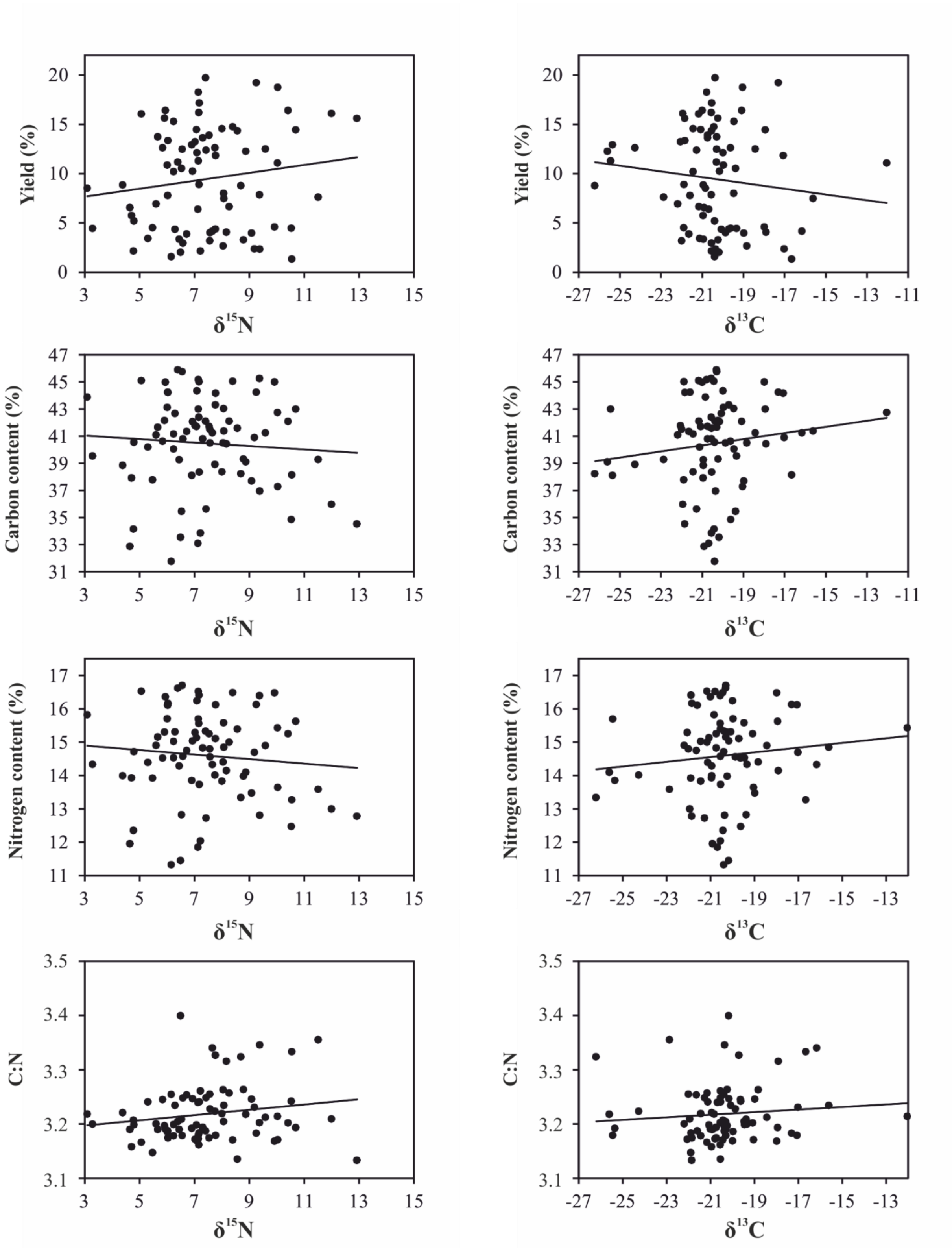


Fig. 8. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in animal sample.

7.1.2 Animal data as a proxy for the isotopic characteristic of environment and human-environmental interaction

For domesticated animals the mean $\delta^{13}C$ value is -19.6±1.8‰ and for wild animals is -20.9±0.3‰ (p=0.071). The mean $\delta^{15}N$ value for domesticated animals is 7.4±1.7‰ and for wild animals is 5.3±1.2‰ (p=0.019). The mean $\delta^{13}C$ value for the fish group is -24.5±1.6‰ and the mean $\delta^{15}N$ value is 9.1±2.8‰. The basic descriptive statistics for distinct species (when the number of samples is ≥ 5) are shown in Table 5. In the case of fish (including carp, pike, dace and 4 samples of undetermined species) and "wild herbivores" (including 4 red deer and 1 roe deer) the results are presented for these wider groups due to the low number of individuals of distinct species. In several cases (dog, horse, bear, beaver, wild boar) only 1-4 samples were available for analysis so their isotopic values are neither presented in Table 5 nor included in the statistical analysis. These data are presented only in Figure 9 and Table A1 in order to complete a picture of potential dietary sources of the Great Moravian population.

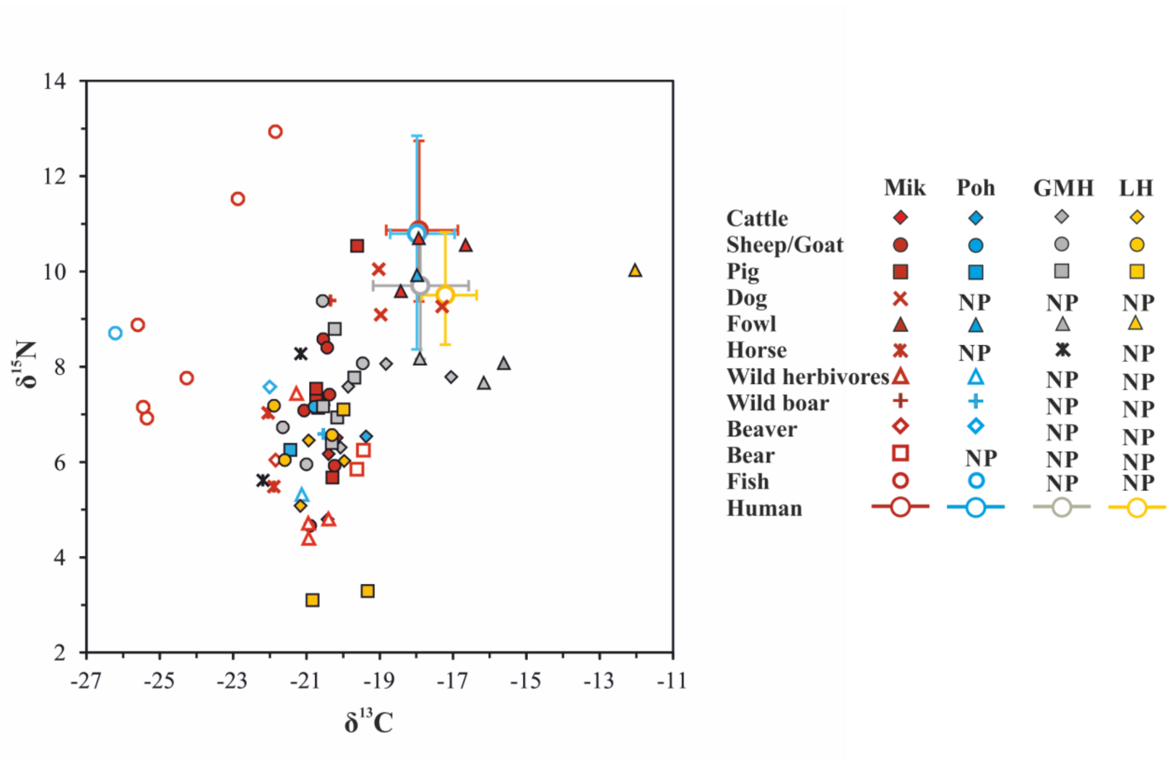


Fig. 9. Animal and human (mean, percentile 2.5 and 97.5) isotopic data for all sites. Mik = Mikulčice; POH = Pohansko; GMH = Great Moravian hinterland; LH = late Hillfort sample; NP = not present.

TABLE 5. Basic statistics of animal sample[a]

Species (N)		Yield (%)	Nitrogen Content	Carbon Content	C:N	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)
Cattle (N=13)	**Min**	1.6	11.3	31.7	3.17	4.8	-21.2
	1st quartile	2.1	12.3	34.1	3.19	6.2	-20.5
	Mean	6.8	13.9	38.6	3.23	6.6	-19.9
	SD	5.7	1.8	4.5	0.06	1.0	1.1
	Median	3.9	14.3	39.3	3.23	6.5	-20.2
	3rd quartile	11.8	15.7	43.1	3.23	7.6	-19.4
	Max	17.1	16.5	45.1	3.40	8.1	-17.1
Sheep/Goat (N=14)	**Min**	3.8	11.9	32.9	3.13	4.7	-21.9
	1st quartile	7.9	15.3	41.8	3.18	6.2	-21.0
	Mean	12.0	15.6	42.9	3.19	7.1	-20.8
	SD	4.9	1.2	3.3	0.03	1.3	0.7
	Median	13.4	15.8	43.6	3.19	7.1	-20.7
	3rd quartile	15.4	16.4	45.0	3.20	7.9	-20.4
	Max	19.7	16.7	45.7	3.25	9.4	-19.5
Pig (N=14)	**Min**	3.3	11.8	33.1	3.16	3.1	-21.4
	1st quartile	4.9	14.4	39.8	3.18	6.3	-20.7
	Mean	9.5	14.8	41.0	3.21	6.8	-20.3
	SD	4.3	1.3	3.5	0.05	1.9	0.6
	Median	10.2	15.1	41.7	3.20	7.1	-20.3
	3rd quartile	13.2	15.5	43.1	3.24	7.5	-20.0
	Max	16.2	16.6	45.9	3.33	10.5	-19.3
Fowl (N=8)	**Min**	1.3	13.3	38.1	3.17	7.7	-18.4
	1st quartile	4.1	14.3	41.0	3.21	8.1	-17.9
	Mean	7.4	14.9	41.6	3.25	9.3	-16.6
	SD	4.7	1.0	2.0	0.07	1.2	2.1
	Median	6.0	14.9	41.3	3.22	9.8	-17.3
	3rd quartile	11.4	15.5	42.8	3.32	10.2	-16.0
	Max	14.4	16.5	45.0	3.34	10.7	-12.0
Fish (N=7)	**Min**	7.6	12.8	34.5	3.13	6.9	-26.2
	1st quartile	10.0	13.5	38.2	3.19	7.5	-25.5
	Mean	11.6	13.9	38.7	3.23	9.1	-24.5
	SD	2.7	0.9	2.5	0.08	2.3	1.6
	Median	12.2	13.8	38.9	3.22	8.7	-25.4
	3rd quartile	12.7	14.1	39.2	3.27	10.2	-23.6
	Max	15.6	15.7	43.0	3.35	12.9	-21.8
Wild herbivores (N=5)	**Min**	3.4	12.7	35.6	3.16	4.4	-21.3
	1st quartile	5.2	13.9	37.9	3.20	4.7	-21.1
	Mean	7.1	13.9	38.6	3.21	5.3	-20.9
	SD	3.5	0.8	2.00	0.04	1.2	0.3
	Median	5.7	14.0	38.8	3.22	4.8	-20.9
	3rd quartile	8.8	14.4	40.2	3.24	5.3	-20.9
	Max	12.4	14.7	40.5	3.25	7.4	-20.4

[a] only groups including 5 or more individuals included; N = No. of samples.

The $\delta^{13}C$ values of the wild animals, as well as most of the cows, pigs and sheep/goats, fall well within the range of values expected for individuals living in temperate and C_3-plant environments. One cow (MUTF10) however exhibits $\delta^{13}C$ value of

-17.05‰ which suggests substantial millet consumption. Several other samples (Table A1, Fig. 9) cluster around -19‰, which may again suggest the minor use of millet as the supplementary fodder (Fuller et al. 2012a).

When compared to other studies focused on the medieval period in a Central European context (Table 6, Fig. 10), our samples show slightly higher $\delta^{13}C$ values than is typical for other sites from this area.

TABLE 6. Comparative data set of animal isotopic values[a]

Region	**Site**	**Time period**	**N**	**Species**	**Ref.**
Turkey	Sagalassos	9th-12th	68	C(26), P(19), S/G(11), WH(12),	(Fuller et al. 2012a)
Germany (Bavaria)	more sites	6th -7th	43	C(16), P(11), S/G(10), H(6)	(Hakenbeck et al. 2010)
Czech Republic (Great Moravia)	Mikulčice - Kostelisko	9th-10th	18	C(4), S/G(4), P(5), D(2), H(2)	(Halffman and Velemínský 2015)
Germany (Central Germany)	more sites	5th -6th	15	C(6), P(4), S/G(1), Fo(2), H(2)	(Knipper et al. 2013)
Czech Republic	Kutná Hora	La-Tène period	3	C(1), P(1), H(1)	(Le Huray and Schutkowski 2005)
Croatia	more sites	7th-9th	29	C(5),P(2), S/G(6), D(13), H(3)	(Lightfoot et al. 2012)
Austria	Voders	6th -7th	20	C(7), P(6), S/G(4), Fo(2), H(1)	(McGlynn 2007)
Poland	Giecz, Kaldus	11th-13th	37	C(6), P(4), S/G(2), WH(5), Fi(17), Fo(2), D(1)	(Reitsema et al. 2010; 2013)

[a]N = total No. of samples; C = cattle; P = pig; S/G = sheep/goat; D = dog; Fo = fowl; H = Horse; WH = wild herbivores; WB = wild boar; B = bear; Fi = fish; Be = beaver, No. of samples in parentheses.

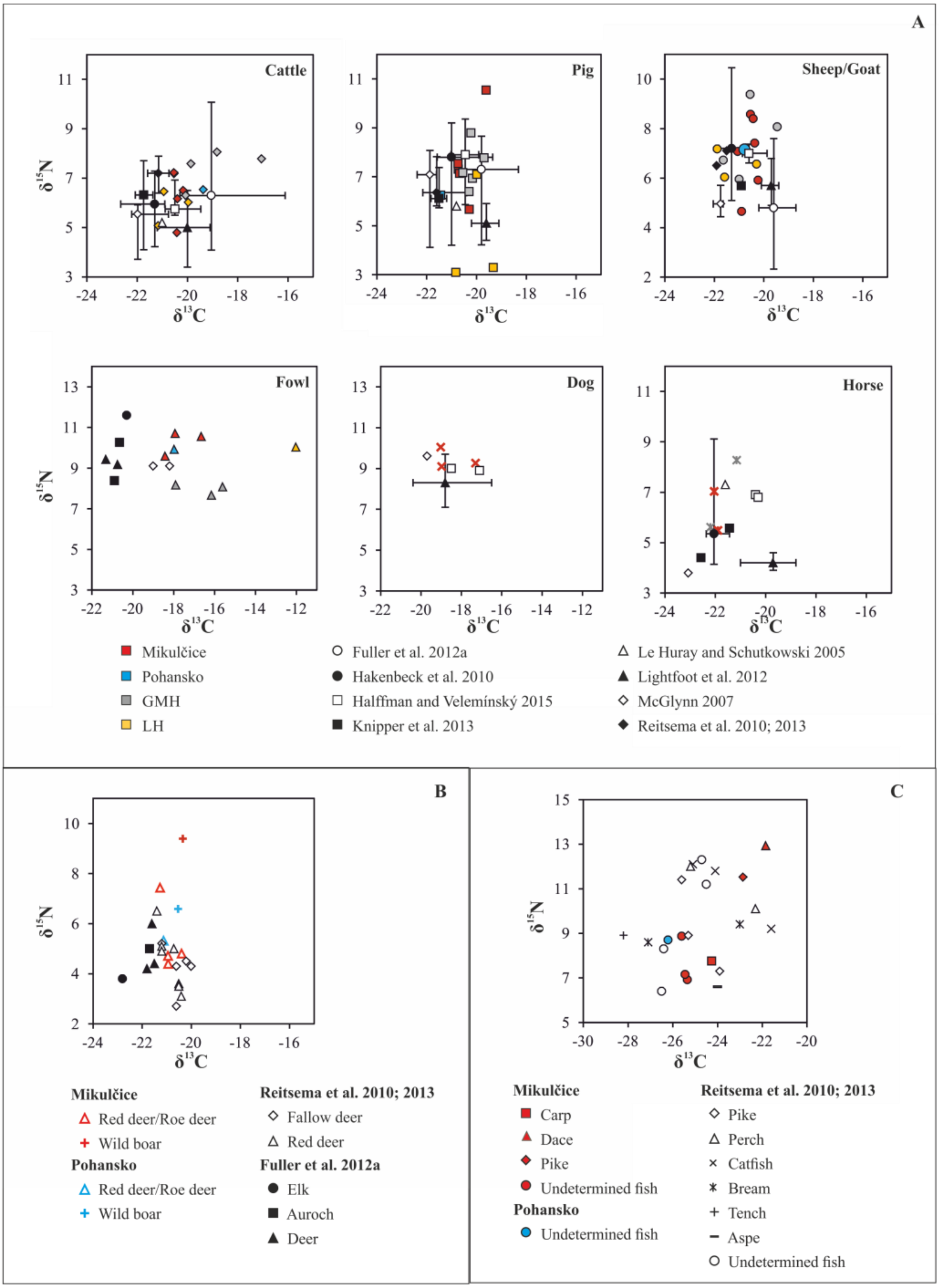


Fig. 10. Animal data in comparison with other European medieval sites (median, percentile 2.5 and 97.5 when No. of samples higher than 5). A: domesticated animals; B: wild herbivores; C: fish. GMH = Great Moravian hinterland; LH = late Hillfort sample.

In fact, carbon isotopic values of Moravian animals range between those of Central European sites (Hakenbeck et al. 2010; Knipper et al. 2013; McGlyn 2007; Reitsema et al. 2010; 2013) and those from the sample of medieval Croatia or Turkey (Fuller et al. 2012a; Lightfoot et al. 2012). For the sample from Turkey the use of millet as a fodder is suggested (Fuller et al. 2012a). This could indicate that, in a Great Moravian context, millet could also have been used as a supplementary fodder. However, similar carbon isotopic values were observed also in wild animals, where the regular consumption of C_4 plants is highly improbable. Moreover, the study of the La Tène population of Bohemia shows a similar range of carbon isotopic values for the animal sample (Fig. 10) (Le Huray and Schutkowski 2005). Though the number of samples is very low in both studies, available data suggest that this range in carbon isotopic values may be typical for the area of today's Czech Republic. Future research is needed in order to tease out this question thoroughly. For the $\delta^{15}N$, Reitsema et al. (2013) consider isotopic values similar to those of this study being "relatively high when compared to other European regions". However from the Figure 10 it clearly appears that $\delta^{15}N$ values of domesticated herbivores and omnivores are typical for the Central European context. Our data does overlap well with those obtained by Halffman and Velemínský (2015) for the Mikulčice-Kostelisko suburb, which ensures the good comparability of human isotopic data between both studies.

At first glance, the isotopic values of domesticated animals are highly dichotomous, with dogs and fowl (mean $\delta^{13}C$ = -17.1±1.8; $\delta^{15}N$ = 9.3±0.3) being clearly separated from other domesticated species in showing a higher trophic position as well as substantial consumption of millet (p=<0.001 for both carbon and nitrogen). This type of dichotomy in values of domesticated animals is quite common (e.g. Fuller et al. 2012a; Keenleyside et al. 2009; Lightfoot et al. 2012; Reitsema et al. 2013) resulting from the close co-habitation of certain species (mainly dogs and fowl) with humans. Kept near households, dogs and fowl consumed scraps of the same foods as humans once they were discarded, and potentially also animal and/or human excrement (Guiry 2013; Reitsema et al. 2013). In the case of fowl, also the consumption of insects, worms and grubs could have augmented their diet with protein rich foods (McGlynn 2007). Moreover, the original paper by Schoeninger and DeNiro (1984) mentions the slightly elevated nitrogen isotopic values to be typical for avian collagen. However, putting aside the $\delta^{15}N$, which may be, in the case of fowl, influenced by the above-mentioned factors, the substantial consumption of millet seems to be a common dietary feature for these two animal species. As such, millet consumption appears to be a clear indicator of a “household ecological niche” in the Great Moravian as well as late Hillfort period.

As outlined in the Introduction (see Chapter 1), the isotopic values of pigs were of great importance in this study as an indicator of the degree of urbanization. Though a small sample size, it appears that the majority of Great Moravian pigs (with one exception) shared the ecological niche with domesticated herbivores (p=0.884 for $\delta^{13}C$ and 0.696 for $\delta^{15}N$) rather than with dogs and fowl. This suggests that in Great Moravian centers pigs were still kept in the traditional manner, being allowed to feed freely on local vegetation (Poláček 2008a). The same type of breeding is suggested for pigs from various medieval sites in Germany, Poland and England continuing up to the 13th century (Hammond and O’Connor 2013; Knipper et al. 2013; Reitsema et al. 2013). The natural conditions of Great Moravian centers, particularly the character of the flood plain, may have sustained the maintenance of the traditional type of breeding despite the growing population of the site. Surrounded by a river, inhabitants may have used numerous small islands, covered by woods, as naturally fenced pastures (Poláček 2008a). Although the comparison of isotopic values from ruminants *vs*. pig bone values can be problematic (Halley and Rosvold 2014), the clear absence of a millet signal in Great Moravian as well as late Hillfort pigs excludes them clearly from the „household ecological niche” as represented by dogs and fowl. Even the only outlier (MIKF26, $\delta^{13}C$ = -19.6; $\delta^{15}N$ = 10.5) differs from the rest of the sample only by increased $\delta^{15}N$, which suggests a higher percentage of animal protein in its diet. There is no indication of the consumption of millet which makes the “backyard” type of breeding practices also improbable for this case.

When chickens and dogs are omitted, both $\delta^{13}C$ (-20.3±0.8) and $\delta^{15}N$ (6.8±1.4) values for the remaining domesticated animals are statistically undistinguishable from the wild animals (p=0.101 for $\delta^{13}C$ and 0.220 for $\delta^{15}N$). The absence of a systematic isotopic difference between wild and domesticated animals contrasts with the results of Reitsema et al. (2013) for the 11th century proto-urban center of Kaldus. The authors of that study attributed the observed differences to different canopy shading (with domesticated animals living in more open habitats) as well as to special land management (manuring, ploughing) and husbandry practices. Analogically, the absence of any observable differences in our sample may sustain the proposed hypothesis of the use of forested river islands, with no other agricultural use, as naturally fenced pastures at least for the sample of Great Moravian centers. However, the observations for Kaldus are based on a very low number of individuals as is the case of our study. Though the canopy effect seems to be observable for both modern and ancient ungulates of temperate ecosystems (Drucker et al. 2008) the very low number of sampled wild ruminants (or their complete omission) is a common feature in dietary reconstruction of medieval populations (Hakenbeck et al. 2010; Halffman and Velemínský 2015; Knipper et al. 2013; Reitsema et al. 2010). As clearly demonstrated by papers from the field of animal ecology, there is a wide variability and clear niche divisions among distinct species of ruminants, which is reflected in their isotopic values (Drucker et al. 2010; Stewart et al. 2003). In these circumstances, a much larger sample (escpecially in case of wild ruminants) would be needed to interpret the isotopic dichotomy (or its absence in the case of the Great Moravian sample) between wild and domesticated animals as a reflection of husbandry practices.

To mention briefly another particularities of animal samples: within domesticated animals, horses (N=3) show a slightly lower $\delta^{13}C$ than other species, though the low number of individuals precluded any statistical analysis. However this pattern is observed among many populations from the Iron Age to medieval period (Hakenbeck et al. 2010; Knipper et al. 2013; Privat et al. 2002; Stevens et al. 2010; Strott 2007), suggesting it to be due to the particularities in the horse metabolism (Hamilton et al. 2009; Hedges 2003). On the other hand, horse data published by Halffman and Velemínský (2015) for Mikulčice - Kostelisko did not show this pattern. The horse is the only species for which the data of both studies do not overlap. Data by Halffman and Velemínský (2015) show one of the most positive horse values published for the Central European context (Fig. 10). Therefore, looking at the results of both studies as a combined sample, the data may reflect a mix of fodder from a wider range of different habitats, which may suggest either variable feeding practices or the importation of horses from another area.

From wild animals, bears and beavers appear to have specific isotopic values which reflect their particular habitat and ecology (Liden and Angerbjörn 1999; Nelson et al. 1998). This may be of special importance for the dietary reconstruction of Pohansko, where both species were found in surprisingly high quantities. However, as appears from Figure 9, their comparatively low and high carbon isotopic values are likely to cancel each other out in the carbon isotopic signal. Although we may not exclude the influence on isotopic data of certain individuals due to their particular dietary preferences, we consider the substantial impact at the population level as improbable.

Statistical analysis on animal data was performed in order to discover potential differences in environmental conditions or husbandry and land management practices between different contexts (floodplain *vs.* hinterland) and chronologies (Great Moravian *vs.* late Hillfort period). As noted previously, the unique environment of the flood plain offered suitable, naturally bounded areas of pastures in the woodland where the animals could be kept in an only partially domesticated manner. These practices could influence isotopic values together with the environmental particularities of the floodplain such as different humidity or canopy shading. On the other hand, in the close vicinity of rapidly growing centers, unprecedented anthropogenic impact (e.g. deforestation, intensive herding or manuring) may have influenced isotopic values at the base of the food chain. But since our knowledge of the natural condition of the areas outside the floodplain is very limited (Dreslerová et al. 2013) it makes it difficult to deliver concrete hypotheses.

In each case, as our data clearly presents, if there were any differences in natural conditions between both contexts they were not reflected in the isotopic signal of animals that were slaughtered/eaten in GM centers and those from their hinterland ($p=0.224$ for $\delta^{13}C$ and 0.938 for $\delta^{15}N$, respective $p=0.182$ for $\delta^{13}C$ and 0.072 for $\delta^{15}N$ when dogs and fowl are excluded). The only exception to this trend is the “household” group of dogs and fowl which shows a statistically significant difference in nitrogen isotopic values ($p=0.027$). These, however, most probably only reflect the analogical difference in human dietary behavior and the subsequent distinct composition of human waste. Human data will be discussed separately in the next chapter.

In order to discover potential differences in isotopic background at the chronological scale, we have compared the values of domesticated animals from the Great Moravian and late Hillfort periods. This analysis showed a statistically significant difference in $\delta^{15}N$ values ($p=0.173$ for $\delta^{13}C$ and 0.009 for $\delta^{15}N$) which persists even when dogs and fowl are excluded from the analysis ($p=0.343$ for $\delta^{13}C$ and 0.010 for $\delta^{15}N$). As evident from the Figure 9, this difference is caused mainly by the relatively low values of two late Hillfort pigs. However, with only three late Hillfort pigs (which all come from one site) it is impossible to propose any explanation of this trend. But even though this could be simply the relict of the small sample size, it should be kept in mind when interpreting human isotopic values.

Isotopic values of fish (N=7, Fig. 11) are highly variable (24.5±1.6‰ for $\delta^{13}C$ and 9.1±2.8‰ for $\delta^{15}N$).

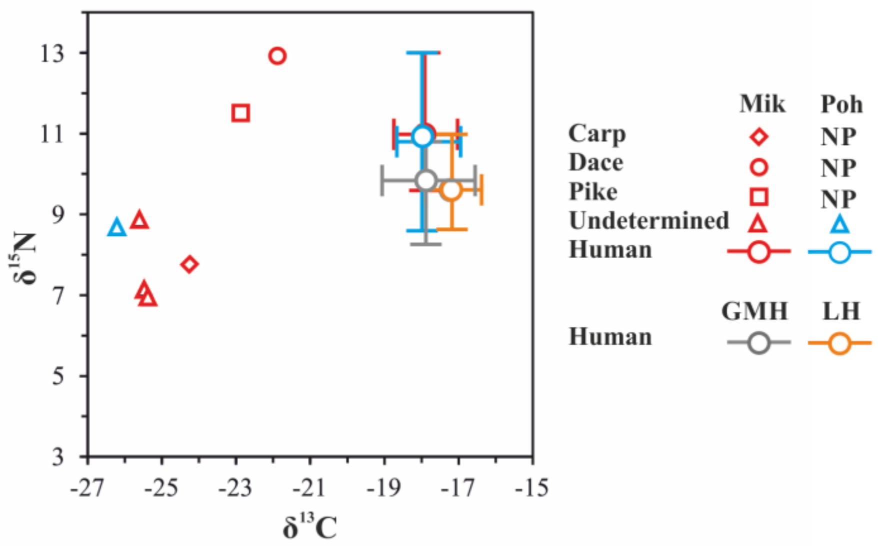


Fig. 11. Fish and human (mean, percentile 2.5 and 97.5) isotopic data for all sites; Mik = Mikulčice; POH = Pohansko; GMH = Great Moravian hinterland; LH = late Hillfort sample; NP = not present.

This high diversity of fish isotopic data may reflect the character of the flood plain ecosystem of the Morava and Dyje Rivers. Being significantly connected to terrestrial habitats and groundwater, river–flood plain systems generally exhibit great habitat and microhabitat diversity (Ward et al. 1999). It was proved that differences in decomposition and respiration processes between the flood plain and the main river channel cause $\delta^{13}C$ signatures to become gradually enriched from shore to channel (Barth and Veizer 1999; Bertrand et al. 2011; Keough et al. 1996; 1998). Moreover, flood plain food webs are often substantially supported by both phytoplankton and periphyton which are two isotopically distinct food sources (Hecky and Hesslein 1995). The use of a wide range of habitats between the flood plain and the main river channel may cause the huge variability of carbon isotopic values even within a single species (Bertrand et al. 2011).

In fact, the high diversity of fish data is typical for European freshwater species (Fuller et al. 2012b; Reitsema et al. 2013; Vika and Theodoropoulou 2012). Fish isotopic values of our sample are similar to those reported by Reitsema et al. (2013) in the context of medieval Poland (Fig. 10C).

The wide variability of fish data may cause potential problems for the dietary reconstruction. Examples of so-called fish “masquerading” were documented (Reitsema et al. 2013), with fish having similar values as terrestrial animals. Particularly the $\delta^{13}C$ values often appear quite “terrestrially” in a number of isotopic studies, where only increased

$\delta^{15}N$ suggest the substantial consumption of freshwater products (Fischer et al. 2007; Katzenberg and Weber 1999; Privat 2004; Vika et al. 2009). In this light it is important that the mean values of our sample differ significantly from terrestrial animals ($p<0.001$ for $\delta^{13}C$ and 0.005 for $\delta^{15}N$ when dogs and fowl are excluded), although two of the seven analyzed fish show carbon isotopic values close to those of terrestrial animals. However these come from the remains of pike (MIKF40) and dace (MIKF42), while the majority of identified fish remains in the Great Moravian context are those of carp (~70% of all findings in Mikulčice). Pike represented about 5% of identified fish remains from Mikulčice and dace was found only sporadically (Zawada 2003). The only carp sampled (MIKF39) show clearly distinct values ($\delta^{13}C$ = -24.3; $\delta^{15}N$ = 7.8). Although the wide variability of fish isotopic values observed even in a single species (Bertrand et al. 2011; Fuller et al. 2012b) encourages caution when deriving any conclusions based on a single sample of each species, we still would consider it improbable if a significant consumption fish was not reflected in human $\delta^{13}C$ values.

7.1.3 Stable isotope analysis of sulphur in animal samples

The huge variability of fish carbon and nitrogen isotopic data suggested that it may be problematic to estimate the importance of aquatic resources in the Great Moravian diet based solely on these isotopic systems. In these circumstances, the next logical step seemed to be to evaluate the potential of the isotopic analysis of sulphur in the context of Great Moravia.

Due to the low percentage of sulphur in bone collagen, quite a high amount of collagen (approx. 10mg) was requested for the mass spectrometry. For this reason, not all the samples could be analyzed and not all the species are represented equally in this sub-sample. For example only one sample of cattle provided sufficient collagen for the isotopic analysis of sulphur.

All the samples (N=15) of mammal and avian (represented by fowl) collagen samples met the criteria by Nehlich and Richards (2009) for well-preserved collagen. In fish, however, the results were much less convincing. Four of a total of seven fish samples (MIKF35, MIKF38, MIKF39, MIKF41) show the C:S ratio as out of the recommended range (Table A2, Fig. 12). Moreover in one case (MIKF41) the N:S ratio was also slightly below the recommended minimum. In all the cases, the percentage of sulphur was too low for the corresponding percentage of carbon and nitrogen. In three of four cases, however, the value was close to the recommended range (Fig. 12). At the same time, Nehlich et al.

(2010; 2011) consider even more outlying values as acceptable for well-preserved collagen (see Chapter 3 and Fig. 12 for more detail). We have therefore decided not to exclude any of samples from further analysis although the four above mentioned cases will be discussed thoroughly in the light of their suspect percentage of sulphur.

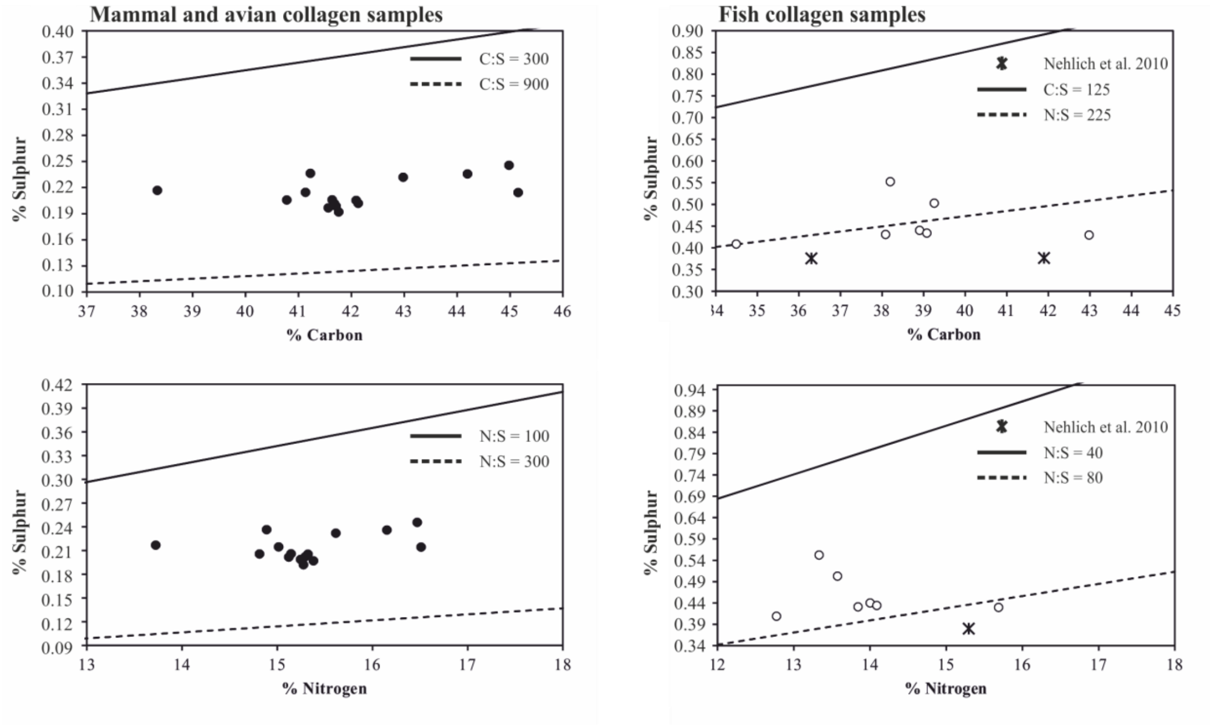


Fig. 12. Relationship between sulphur isotopic values and collagen preservation criteria in animal sample. Samples considered by Nehlich et al. 2010 as well preserved though outside the recommended range marked.

For our pilot study of sulphur isotope values in animal samples, we have proposed two alternative hypotheses: In the ideal case, sulphur isotopic values should discriminate between a terrestrial and aquatic environment. But because of the location of Great Moravian centers in the area of flood plains, an alternative hypothesis was created: Due to the potential effect of riverine sulphur sources on the isotopic values of terrestrial animals (Nehlich et al. 2011), the values of aquatic and terrestrial animals were likely to overlap. But as appears clearly from the Figure 13, the situation in the Great Moravian context is even more complicated: Sulphur isotopic values of fish are highly variable, ranging from -10.3‰ in POHF01 to 12.3‰ in MIKF35. Even when only values observed at the Mikulčice site are considered, the observed variability is still substantial with a minimum of -7.9‰ observed in MIKF42. Apparently, fish values are clustered in two groups with all the terrestrial animals in between. The group of terrestrial animals is clustered around 1‰

with a substantial variability (mean $\delta^{34}S$ = 0.7±3.2‰). When looking at particular species, the values of pigs appear to be more homogenous while sheep and goats show a much higher variability. A similar pattern was also observed by Privat et al. (2007) and may suggest a wider variety of habitats used by sheep and goats. The only sample of cattle shows the lowest values from all the terrestrial animals (MIKF33, $\delta^{34}S$ = -4.2‰). Regrettably, due to the low amount of collagen in other samples of cattle, it is not possible to evaluate whether cattle shared the isotopic pattern with sheep and goats, suggesting their higher mobility and use of distinct habitats.

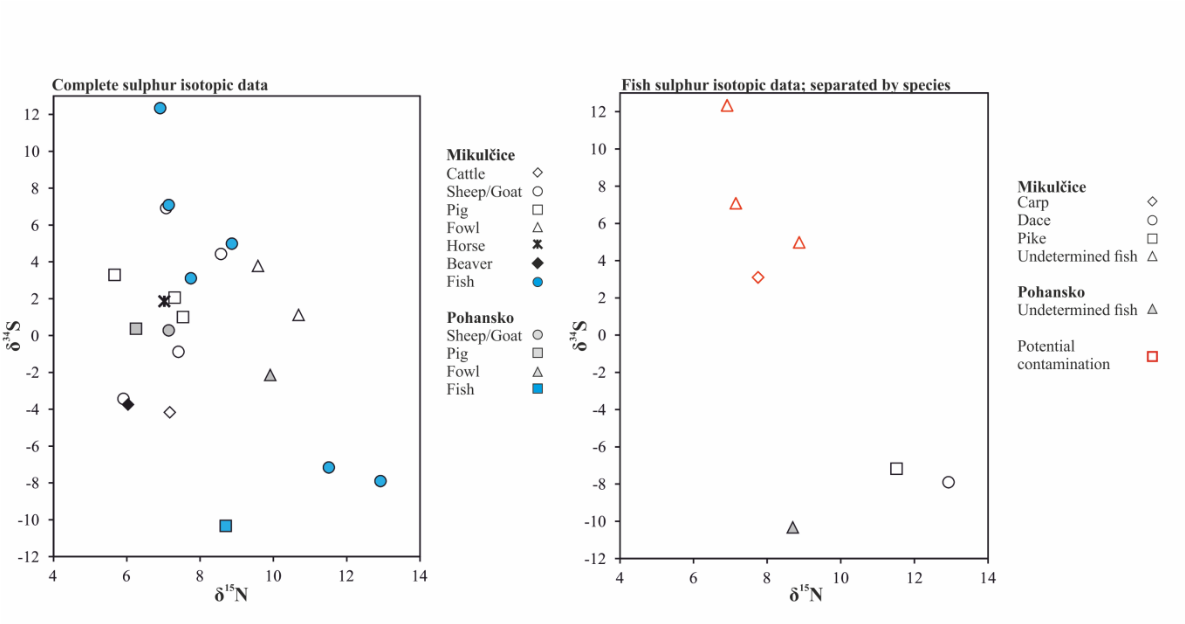


Fig. 13. Complete sulphur isotopic data. Potentially contaminated samples highlighted in red.

As suggested, values of terrestrial animals overlap substantially with the first group of fish (Group 1: showing positive sulphur values), while the second group of fish (Group 2: showing negative sulphur values) appears to be separate from all the other samples. For this dichotomy in sulphur isotopic values several explanations may be proposed. First, it is interesting to view the data in the light of preservation criteria. All the samples with suspect C:S ratio show positive sulphur values. However, the low number of individuals and above mentioned uncertainties about the validity of sample preservation criteria prevent attributing the observed isotopic pattern to sample diagenesis unequivocally.

Another potential explanation of the observed pattern may lie in the use of different sources for fishing. Theoretically Group 1, which overlaps with terrestrial values may come from the Morava river, while Group 2 may come from another water-way.

Interestingly, the only fish sample from Pohansko (POHF01) shows the negative sulphur values typical for Group 2 as well. This makes the river Dyje, with its source in the distant area of the Bohemian-Moravian Highlands and flowing through Pohansko to the final junction with the Morava south of Mikulčice, a possible source of these fish. However this is disputed by the similar values of terrestrial animals recovered from the flood plain areas of both rivers.

Alternatively the small local waterways (such as Kyjovka or Prušánka in the very neighborhood of Mikulčice) may be the source of fish with distinct isotopic values (probably of Group 1). First, they may spring from similar geological conditions and second, in these small streams, an autochthonous diet (from outside the river) dominates in fish (Trembaczowski 2011), which can make their isotopic signal more “local”.

And finally, as discussed in previous chapter, the environment of floodplain offers a number of distinct habitats with specific ratio of local and alluvial sources of sulphur, which may theoretically result in this high variability within a fish population of a single river site.

To conclude this part: without further enlargement of the fish sample, it is not possible to evaluate the potential influence of diagenesis. When, in accordance with Nehlich et al. (2010; 2011) and Privat et al. (2007) we consider all our data as valid, we may suggest that no single aquatic niche was targeted in Great Moravia suggesting a broad spectrum of fishing strategies and/or trade. In each case, this huge isotopic variability observed in fish samples precludes any use of sulphur in the isotopic reconstruction of the Great Moravian diet.

7.2 Isotopic data of adults

7.2.1 General overview of the Great Moravian diet

Human data (Table A3, Fig. 14) shows that the Great Moravian population had a terrestrial diet with a substantial proportion of C_4 plants. The comparison with faunal data ($\Delta^{13}C_{human\text{-}fauna}$ = 2.26-2.53) suggests the direct consumption of millet (most probably in the form of porridge), although the consumption of eggs and poultry may also have contributed to the observed values. From the presented data it appears that the consumption of fish did not play an important role in the Great Moravian diet. Hypothetically the intake of millet (and eggs and meat from millet fed fowl) in combination with freshwater fish may have caused the low and high carbon isotope values to cancel each other out and thus imitate the C_3 terrestrial signal. But $\delta^{15}N$ values oppose this scenario. The spacing in nitrogen isotopic values between human and fauna ($\Delta^{15}N_{human-fauna}$) range from 2.3-2.6 in GMH sample to 3.4-3.8 in GMC sites. This is significantly lower than in populations substantially reliant on freshwater fish for which the $\Delta^{15}N_{human-fauna}$ of 5 or more are typical (Katzenberg and Weber 1999; Rutgers et al. 2009). Nonetheless we cannot exclude some input of freshwater resources in the diet of some particular individuals, which will later be discussed separately (see Chapter 7.2.6.1 for more details).

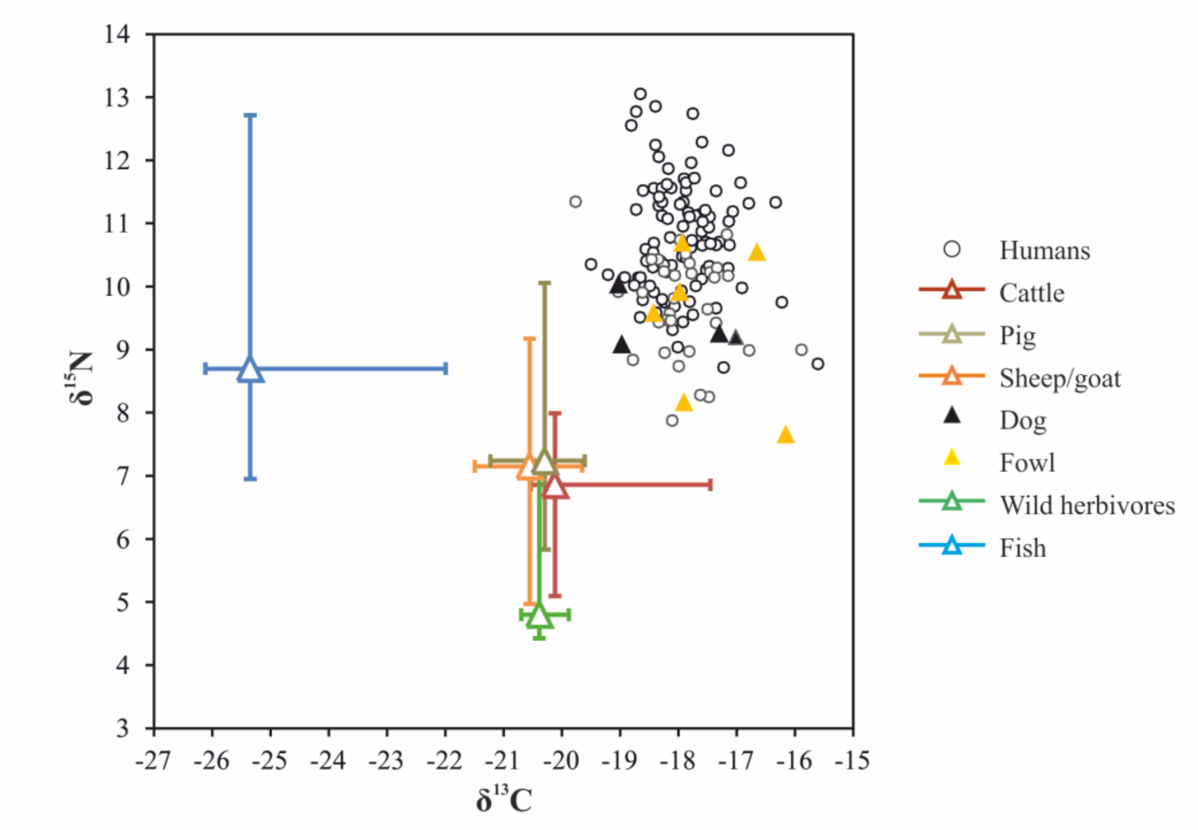


Fig. 14. Human and animal (median, percentile 2.5 and 97.5 with the exception of dogs and fowl) isotopic data for all Great Moravian sites.

When compared to other medieval Central European populations, the relatively high input of millet seems to be characteristic for the Great Moravian population. The mean $\delta^{13}C$ value of Great Moravian humans in this study (N=158) is –17.9±0.6‰, which is comparable to the results obtained by Halffman and Velemínský (2015) for the same population. This is substantially higher than in the 11th century site of Kaldus (mean $\delta^{13}C$ = -18.5±1.0‰), where until now the highest input of millet was observed for early and high medieval Central Europe, except for Great Moravia (Reitsema 2012b). Significant consumption of millet was also observed in early medieval Croatia (Lightfoot et al. 2012).

TABLE 7. Human bone collagen $\delta^{13}C$ and $\delta^{15}N$ (mean ± 1 standard deviation) and human-faunal offsets from medieval sites in Central Europe

Region	Site	Time period	N	$\delta^{13}C$	$\delta^{15}N$	$\Delta^{13}C_{human-fauna}$ [a]	$\Delta^{15}N_{human-fauna}$ [a]	Ref.
Czech Republic	Mikulčice Pohansko, Josefov	9^{th}-10^{th}	158	-17.9±0.6	10.6±1.0	2.3-2.5	3.2-3.6	This study
Germany	more sites	6^{th}-7^{th}	178	-19.6[b]	9.6 [b]	1.4-1.7	1.8-3.7	(Hakenbeck et al. 2010)
Czech Republic	Mikulčice Kostelisko	9^{th}-10^{th}	24	-17.8±0.6	10.0±1.0	2.7-2.8	2.1-4.25	(Halffman and Velemínský 2015)
Germany	more sites	5^{th}-6^{th}	43	-19.8±0.3	9.6±0.9	1.1-1.9	3.3-3.9	(Knipper et al. 2013)
Croatia	Velim Velištak	7^{th}-9^{th}	105	-17.6±0.5	9.5±0.4	2-2.4	3.8-4.5	(Lightfoot et al. 2012)
Croatia	Glavice Gluvine	8^{th}-9^{th}	33	-18.0±0.7	9.2±0.5	1.6-2	3.5-4.2	(Lightfoot et al. 2012)
Croatia	Radašinovci Vinogradine	9^{th}	68	-17.7±0.5	9.7±0.5	1.9-2.3	4.0-4.7	(Lightfoot et al. 2012)
Croatia	Šibenik Sveti Lovre	$9^{th-10th}$	54	-18.4±0.4	10±0.6	1.2-1.6	4.3-5.0	(Lightfoot et al. 2012)
Austria	Voders	6^{th} -7^{th}	103	-20.0±0.4	10.1±0.8	1.8-2.0	3.0-5.1	(McGlynn 2007)
Poland	Kaldus IV	11^{th}	37	-18.5±1.0	10.2±0.8	2.6-3.2	3.0-3.9	(Reitsema 2012b)
Poland	Gruczno 1	12^{th}	34	-19.8±0.4	9.3±0.6	1.3-1.9	2.1-3.0	(Reitsema 2012b)
Poland	Kaldus 1	12^{th}-13^{th}	30	-19.5±0.4	10.2±0.7	1.6-2.2	3.0-3.9	(Reitsema 2012b)
Poland	Gruczno 2	13^{th}-14^{th}	32	-19.9±0.3	9.2±0.8	1.2-1.8	2.0-2.9	(Reitsema 2012b)
Poland	Giecz[c]	11^{th}-12^{th}	24	-18.9±0.4	9.2±0.5	2.2-2.8	2.4-2.9	(Reitsema et al. 2010)

[a] mean value of the spacing in isotopic values between human and fauna. As faunal data, the values of main consumed domesticated species (cattle, sheep/goat, pig) were used. The presented interval comprises differences between species.

[b]only median was given in a concerned paper.

[c]a combined sample of animal data by Reitsema et al. (2010) and Reitsema et al. (2013) was used.

However, due to the above mentioned variation in animal isotopic values (Fig. 10), it would be misleading to assign the variation in human carbon isotopic values among populations to the differing importance of millet in their diet. When comparing human-faunal isotopic offsets among Central European populations (Table 7), Great Moravian values suggest higher input of millet than in the Croatian population. On the contrary, the data of the polish site Kaldus IV shows a slightly higher human-faunal carbon isotopic offset than our Great Moravian sample. However, animal data sets are quite small in all the cases so the power of this testimony is limited.

While Lightfoot et al. (2012) potentially link the increased consumption of millet in Early medieval Croatia to a significant decline in the standard of living after the fall of the Roman Empire, our results do not support this scenario because, in our case, the consumption of millet was observed also in the population of main Great Moravian centers where the presence of elite groups is well documented. On the other hand, our data confirms the hypothesis of the consumption of millet being traditionally linked with Slavic populations (Barford 2001; Halffman and Velemínský 2015; Lightfoot et al. 2012).

7.2.2 Mikulčice

From the Mikulčice site, 70 skeletons were sampled consisting of 34 males and 36 females. Macroscopically, most of the bones from Mikulčice appear well preserved and are dense with an undamaged surface. Most of them were difficult to cut and crush during the sample preparation. All the samples met the criteria for good collagen preservation (DeNiro 1985; van Klinken 1999). The collagen yield rarely falls under 15% and the C:N ratio of the vast majority of samples fall between 3.15 and 3.25. A weak, but statistically significant, correlation was found between nitrogen isotopic values and the C:N ratio (Table 8).

TABLE 8. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{13}C$, $\delta^{15}N$) and collagen preservation criteria in Mikulčice sample[a]

	Yield (%)	**Carbon Content**	**Nitrogen Content**	**C:N**
$\delta^{13}C$	0.337	0.745	0.779	0.776
$\delta^{15}N$	0.397	0.712	0.579	**0.042**

[a] significant at <0.05 boldfaced.

However, the range of the C:N ratio is narrow and there are not any outliers significantly affecting the correlation (Fig. 15). For this reason, no samples were excluded from the further analysis.

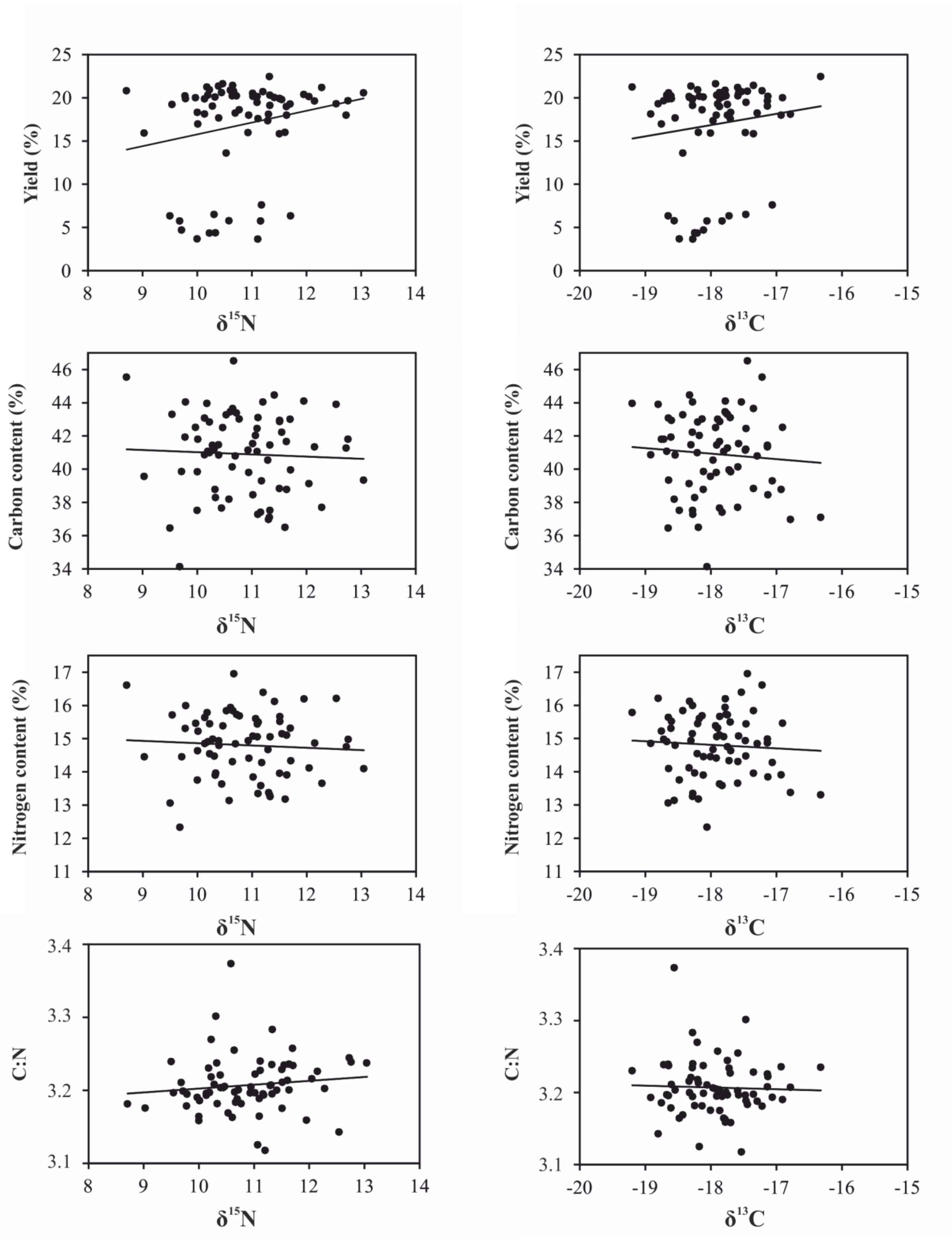


Fig. 15. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in Mikulčice adult sample.

For Mikulčice $\delta^{13}C$ values range from -19.2 to -16.3‰ and $\delta^{15}N$ values range from 8.7 to 13.1‰. In more details, summary data are presented in Table 9.

TABLE 9. Basic statistics of the Mikulčice sample

	All adults		**Males**		**Females**	
	$\delta^{13}C$	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**
N	70	70	34	34	36	36
Min	-19.2	8.7	-19.2	9.8	-18.7	8.7
1st quartile	-18.3	10.2	-18.4	10.5	-18.2	10.0
Mean	-17.9	10.9	-17.8	11.0	-17.9	10.7
SD	0.6	0.9	0.6	0.7	0.5	1.0
Median	-17.9	10.9	-17.9	11.1	-17.9	10.7
3rd quartile	-17.6	11.4	-17.8	11.3	-17.5	11.5
Max	-16.3	13.1	-16.3	12.7	-16.9	13.1
Human *vs.* fauna (Δ)[a]	2.3-2.5	3.5-3.9	2.2-2.5	3.6-4.0	2.3-2.6	3.4-3.7

[a] mean value of the spacing in isotopic values between human and fauna. As faunal data, the values of main consumed domesticated species (cattle, sheep/goat, pig) were used; the presented interval comprises differences between species.

Neither sex nor age-at-death had a statistically significant impact on the human isotopic values of the Mikulčice sample (Tables 10 and 11, Fig. 16). In a further step, data was checked for a potential relationship between isotopic values and markers of socio-economic status. Traditionally the number and quality of grave goods was used as an indicator of the socio-economic status in the GM population (Bigoni et al. 2013; Poláček 2008b; Unzeitigová 2000). In the case of the Mikulčice sample, the statistical analysis revealed that the diet of males buried in well-equipped graves (group A) was significantly enriched in animal protein compared to other groups (Fig. 16). In contrast, no socio-economically motivated differences in female diet were observed. Regrettably, due to the combination of adverse soil properties and the methodology of ancient excavation during the 1950s, no information on other indicators of socio-economic status, such as the presence of a coffin or grave construction are available.

From the individual graves, special attention was paid to grave MIKH46: a male buried in the interior of the so-called 2nd church with rich grave goods including a sword - a rare and exclusive find in the Great Moravian context. His isotopic values ($\delta^{13}C$ =

-18.6‰; $\delta^{15}N$ = 11.5‰) are relatively high (over the 3rd quartile) in nitrogen and low (under the first quartile) in carbon and may suggest a consumption of a certain amount of freshwater fish ($\Delta^{15}N_{human\text{-}fauna}$ = 4.1-4.45). The only other male buried with a sword (MIKH41) shows also above-average $\delta^{15}N$ (11.2‰), but his $\delta^{13}C$ (-17.1‰) is, on the other hand, one of the highest in the whole sample so that in his case the substantial consumption of fish is improbable.

TABLE 10. The impact of biological and socio-economic factors on human isotopic values in the Mikulčice sample, the results of Mann-Whitney /Kruskal-Wallis test[a]

	N				p		
	Males	**Females**	**ND**		**All**	**Males**	**Females**
Sex	34	36	0	**$\delta^{13}C$**	0.167	-	-
				$\delta^{15}N$	0.364	-	-
Age: younger/older than 35	12/22	12/24	0	**$\delta^{13}C$**	0.604	0.471	0.842
				$\delta^{15}N$	0.665	0.756	0.135
Grave goods: A/B/C	15/7/12	12/10/14	0	**$\delta^{13}C$**	0.859	0.481	0.842
				$\delta^{15}N$	0.072	**0.007**	0.599

[a]A = graves with spurs, axes, gold, silver or bronze objects; B = graves with ceramics, glass, Fe and other objects; C = without findings; significant at <0.05 boldfaced.

TABLE 11. Pairwise comparison of groups according to socio-economic status classified according to Unzeitigová (2000)[a]

	All adults		Males		Females	
	$\delta^{15}N$	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**
A-B	0.400	0.988	**0.015**	0.765	0.757	0.859
A-C	0.055	0.933	**0.008**	0.444	0.953	0.869
B-C	0.407	0.848	0.811	0.744	0.579	0.999

[a]A = graves with spurs, axes, gold, silver or bronze objects; B = graves with ceramics, glass, Fe and other objects; C = without findings; significant at <0.05 boldfaced.

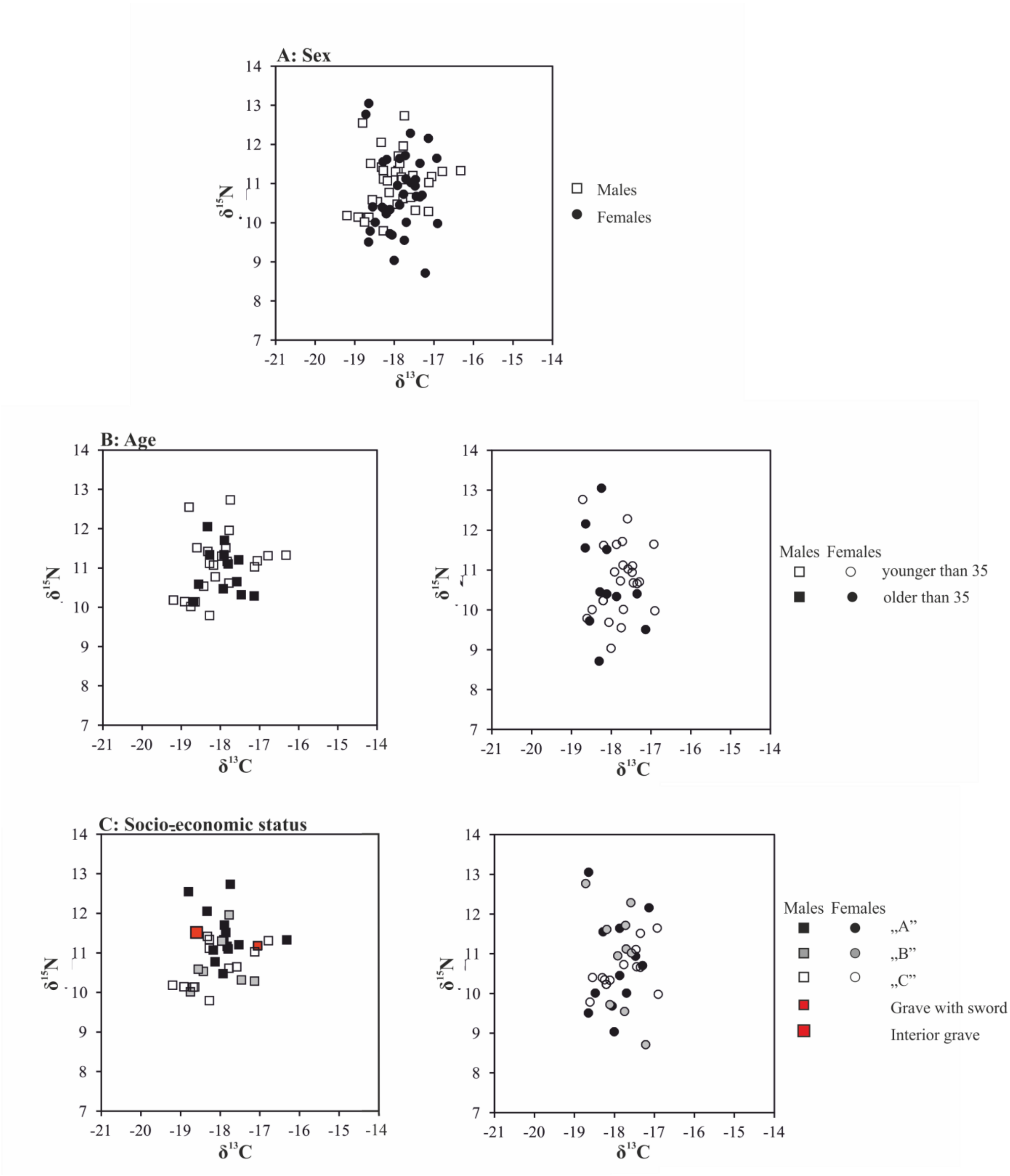


Fig. 16. The relationship between biological and socio-economic factors and human isotopic values in the Mikulčice sample. A = graves with weapons, gold, silver or bronze objects; B = graves with objects of daily use; C = without grave goods.

7.2.3 Pohansko

In the case of Pohansko, the overall preservation is macroscopically the best of all the skeletal collections in this study. Nearly all the bones are dense and difficult to crush with a smooth and undamaged surface. All except for one sample (Table A3) met the criteria for good collagen preservation (DeNiro 1985; van Klinken 1999). The only exception (POHH34) showed a slightly higher percentage of both carbon and nitrogen than the recommended maximum. However, its C:N ratio is within the recommended range and this sample does not significantly affect the correlation between isotopic values and collagen preservation criteria so it was not excluded from the data set. No statistically significant correlation between collagen preservation criteria and isotopic values was observed (Table 12, Fig. 17).

TABLE 12. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{13}C$, $\delta^{15}N$) and collagen preservation criteria in Pohansko sample

	Yield (%)	**Carbon Content**	**Nitrogen Content**	**C:N**
$\delta^{13}C$	0.142	0.904	0.948	0.910
$\delta^{15}N$	0.680	0.125	0.148	0.632

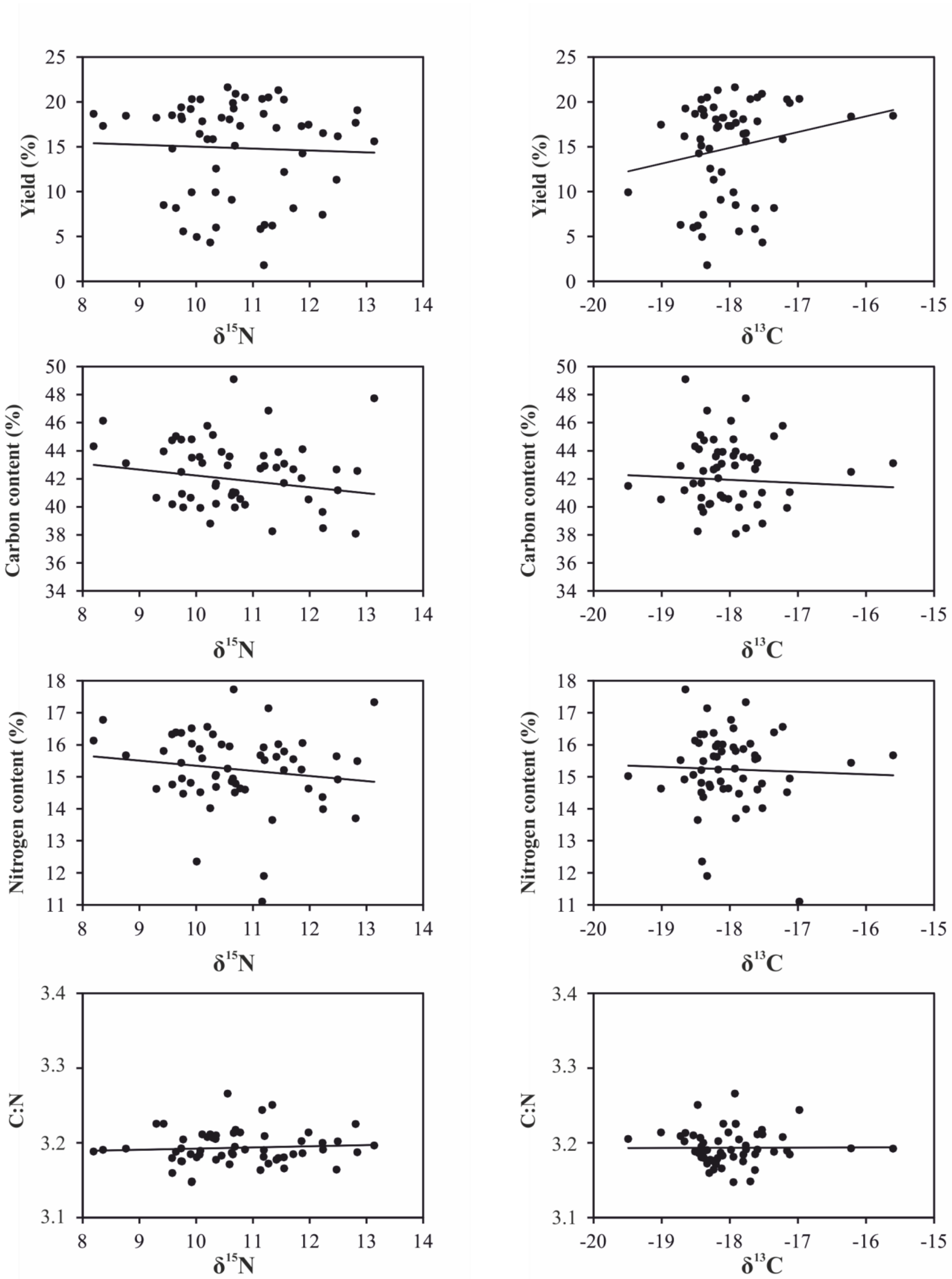


Fig. 17. Relationship between isotopic values (δ^{15}N, δ^{13}C) and collagen preservation criteria in Pohansko adult sample.

In the Pohansko sample, carbon isotopic values range from -19.5 to -15.6‰ and $\delta^{15}N$ values range from 8.2 to 13.1‰. For nitrogen, the highest variability from all the studied sites was observed. More detailed summary data are presented in Table 13.

TABLE 13. Basic statistics of the Pohansko sample

	All		**Males**		**Females**	
	$\delta^{13}C$	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**
N	56	56	31	31	24	24
Min	-19.5	8.2	-19.0	8.4	-19.5	8.2
1st quartile	-18.4	10.1	-18.4	9.8	-18.4	10.2
Mean	-18.0	10.7	-17.9	10.7	-18.1	10.8
SD	0.6	1.1	0.7	1.2	0.5	1.0
Median	-18.1	10.7	-18.0	10.7	-18.2	10.7
3rd quartile	-17.7	11.4	-17.6	11.5	-17.9	11.2
Max	-15.6	13.1	-15.6	13.1	-17.0	12.8
Human *vs.* fauna (Δ)[a]	2.2-2.5	3.4-3.7	2.3-2.6	3.4-3.7	2.1-2.3	3.4-3.7

[a] mean value of the spacing in isotopic values between human and fauna. As faunal data, the values of the main consumed domesticated species (cattle, sheep/goat, pig) were used; the presented interval comprises differences between species.

As in Mikulčice, neither sex nor age-at death had a significant impact on isotopic values in the Pohansko sample (Table 14, Fig. 18).

In Pohansko (in contrast with Mikulčice) no relation was found between isotopic values and the quality of grave goods (Tables 14 and 15). This can, however, be explained by the slight difference in the dating of both sites. The core of the use of Pohansko cemetery lies in the final phase of the existence of Great Moravia. In that time advanced Christianization and the well-established authority of the Church is suggested to have significantly influenced the number as well as character of grave goods. There is no analogy in Pohansko for the exclusive graves (equipped with swords, gold jewelry, elaborately decorated spurs and belt fittings) which were recovered in Mikulčice. Even the grave of the presumed founder of the church (whose location at the main axis of the rotunda clearly reflects the high social status of the buried person) contained no grave goods at all (Macháček et al. 2014; Poláček 2008b).

In Pohansko recent excavation techniques also allowed the evaluation of the impact of other indicators of socio-economic status, such as the presence of a coffin or grave construction (either wooden or stone – these two created one group for the statistical analysis due to the small sample size), or the grave dimensions (length, depth). Additionally, the relationship between isotopic data and grave orientation was examined, which is supposed to have changed during the use of the cemetery. For the purposes of statistical analysis, graves were divided into two groups: west-east oriented and northwest-southeast oriented.

From these characteristics, the presence of grave construction (either wooden or stone) proved to be related to the increased consumption of animal protein in the male sample (Table 14, Figs. 18 and 19). This is an indication, analogically to Mikulčice, that socio-economic status was the important determinant of diet of Pohansko males. Also analogically to Mikulčice, females stand apart from this trend.

TABLE 14. The impact of biological and socio-economic factors on human isotopic values in the Pohansko sample, the results of/Mann-Whitney test/Kruskal-wallis test/linear regression[a]

	N				**p**		
	Males	**Females**	**ND**		**All**	**Males**	**Females**
Sex	31	24	1	**δ^{13}C**	0.190	-	-
				δ^{15}N	0.928	-	-
Age: younger/older than 35	12/19	6/18	1/0	**δ^{13}C**	0.271	0.617	0.581
				δ^{15}N	0.788	0.071	0.770
Grave goods: A/B/C[b]	4/7/20	6/4/14	1/0/0	**δ^{13}C**	0.559	0.364	0.828
				δ^{15}N	0.402	0.402	0.517
Coffin: yes/no	12/19	5/19	0/1	**δ^{13}C**	0.742	0.589	1.000
				δ^{15}N	0.536	0.589	0.406
Construction: yes/no	11/20	9/15	0/1	**δ^{13}C**	0.771	0.730	0.289
				δ^{15}N	**0.001**	**0.004**	0.194
Length of the grave	29	22	0	**δ^{13}C**	-	0.159	0.111
				δ^{15}N	-	0.128	0.269
Depth of the grave	29	23	1	**δ^{13}C**	0.073(0.288)[c]	0.477	0.058(0.268)[c]
				δ^{15}N	0.957	0.754	0.889
Orientation W-E/SW-NE[b]	7/19	4/12	0/1	**δ^{13}C**	0.388	0.320	0.514
				δ^{15}N	0.920	0.377	0.310

[a] significant at <0.05 boldfaced.

[b]A = graves with spurs, axes, gold, silver or bronze objects; B = graves with ceramics, glass, Fe and other objects; C = without findings; W-E = grave oriented west-east, SW-NE = grave oriented southwest-northeast.

[c]after the exlusion of POHH30 (the grave with extreme depth).

TABLE 15. Pairwise comparison of groups according to the socio-economic status in the sample of Pohansko classified according to Unzeitigová (2000)[a]

	All adults		**Males**		**Females**	
	$\delta^{15}N$	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**
A-B	0.627	0.406	0.839	0.339	0.704	0.933
A-C	0.991	0.996	0.503	0.941	0.515	0.958
B-C	0.670	0.628	0.362	0.763	0.844	0.826

[a]A = graves with spurs, axes, gold, silver or bronze objects; B = graves with ceramics, glass, Fe and other objects; C = without findings; significant at <0.05 boldfaced.

From the individual values, our attention was naturally focused on 2 individuals buried in the rotunda interior (POHH29 and POHH36). As shown clearly in the Figure 18, both males shared a diet characterized by high $\delta^{15}N$ (though not the highest in the sample) and relatively low $\delta^{13}C$ values. Their dietary characteristics are similar to those of the only sample from the Mikulčice 2nd church. Another extraordinary grave is that of POHH30: a young female buried in a grave of excessive dimensions. Her nitrogen isotopic values (11.2‰) are located in the 3rd quartile of the Pohansko sample. Her carbon value (-17.0‰) is the highest for all the Pohansko females. It is however not so extraordinarily high as to propose some hypotheses about, for example, the foreign origin of this female. Certainly, she did not share the dietary pattern of the high status individuals from the interior graves.

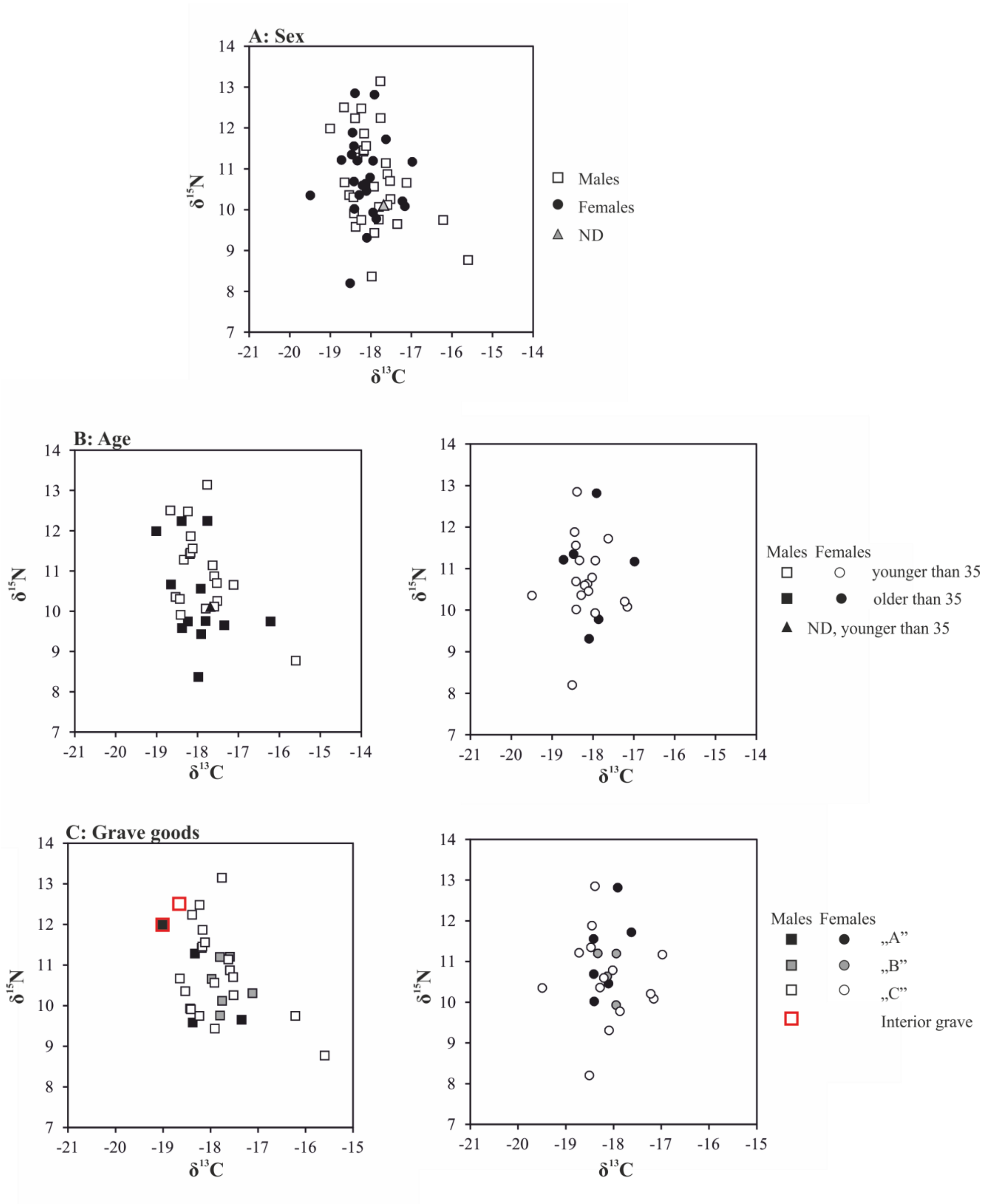


Fig. 18. The relationship between biological and socio-economic factors and human isotopic values in the Pohansko sample. A = graves with weapons, gold, silver or bronze objects; B = graves with objects of daily use; C = without grave goods; ND = undetermined sex.

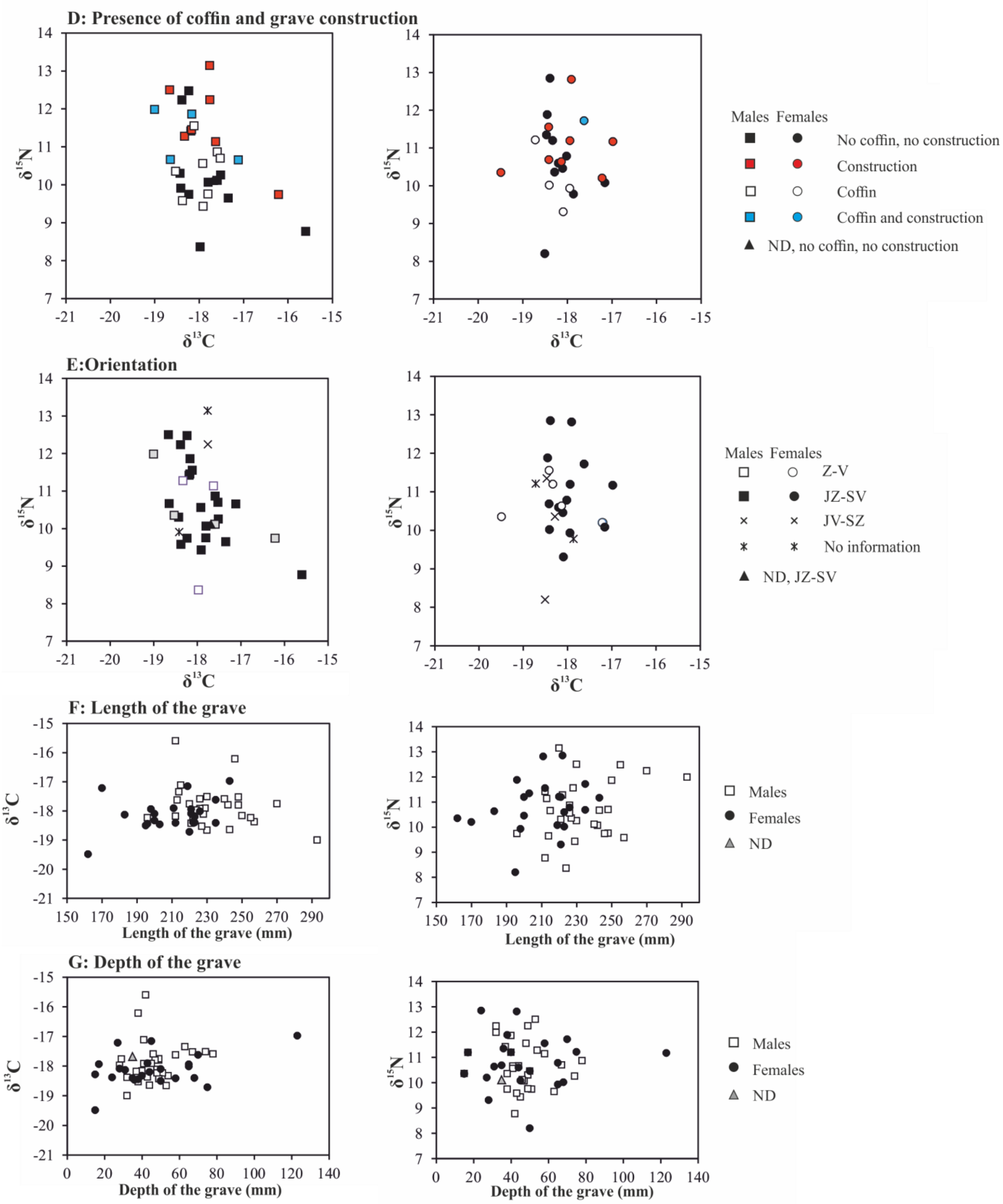


Fig. 19. The relationship between archaeological data and human isotopic values in the Pohansko sample.

7.2.4 Josefov I

In comparison with Mikulčice, most of the Josefov bones were less dense, often appearing dry and chalky with a porous surface. However, all the samples met the criteria for good collagen preservation (DeNiro 1985; van Klinken 1999). But again, a statistically significant correlation was observed between nitrogen isotopic values and the C:N ratio (Table 16). But as in case of Mikulčice the range of the C:N ratio is narrow (ranging from 3.2 to 3.4) and there are no outliers significantly affecting the correlation (Fig. 20). As a result of this, again no samples were excluded from the further analysis.

TABLE 16. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{13}C$, $\delta^{15}N$) and collagen preservation criteria in Josefov I sample[a]

	Yield (%)	Carbon Content	Nitrogen Content	C:N
$\delta^{13}C$	0.474	0.226	0.299	0.474
$\delta^{15}N$	0.147	0.528	0.383	**0.010**

[a]significant at <0.05 boldfaced.

In the sample of Josefov I, carbon isotopic values range from -19.8 to -15.9‰ and $\delta^{15}N$ values range from 7.9 to 11.3‰. More detailed summary data are presented in Table 17.

TABLE 17. Basic statistics of the Josefov I sample

	All adults		**Males**		**Females**	
	$\delta^{13}C$	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**
N	32	32	12	12	20	20
Min	-19.8	7.9	-19.8	7.9	-18.8	8.2
1st quartile	-18.2	9.0	-18.4	10.1	-18.1	9.0
Mean	-17.9	9.7	-18.3	10.1	-17.7	9.5
SD	0.7	0.7	0.6	0.8	0.7	0.7
Median	-18.0	9.9	-18.1	10.2	-17.7	9.4
3rd quartile	-17.5	10.3	-17.9	10.4	-17.3	10.0
Max	-15.9	11.3	-17.5	11.3	-15.9	10.8
Human *vs.* fauna (Δ)[a]	2.3-2.6	2.3-2.6	2.0-2.2	2.7-3.1	2.5-2.8	2.1-2.4

[a] mean value of the spacing in isotopic values between human and fauna. As faunal data, the values of the main consumed domesticated species (cattle, sheep/goat, pig) were used; the presented interval comprises differences between species.

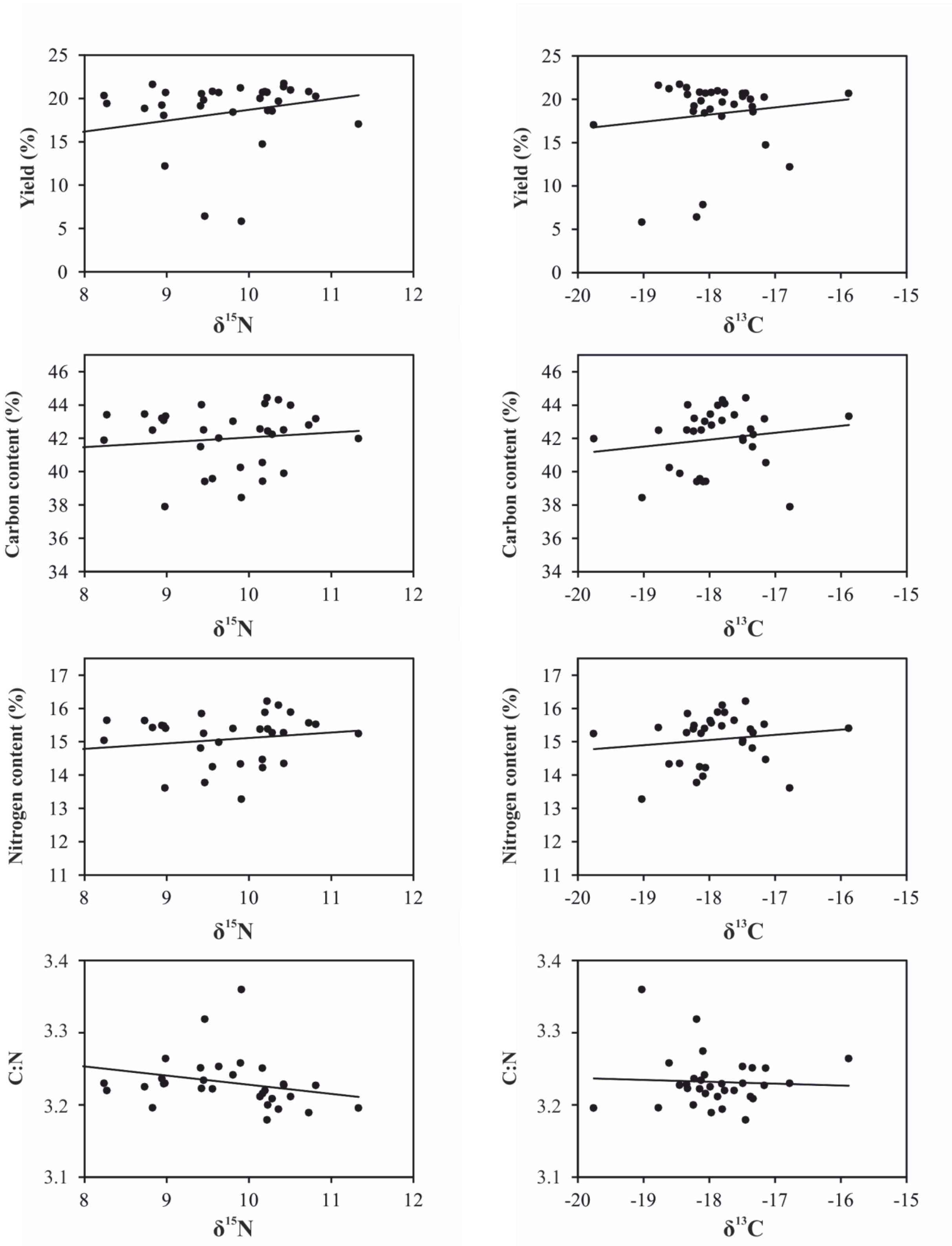


Fig. 20. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in Josefov I adult sample.

The diet of the inhabitants of Josefov during the Great Moravian period has two main characteristics: except for a relatively low consumption of animal protein, which will be discussed later in relation to other sites, Josefov I, is the only one of the Great Moravian sites that shows a clear isotopic difference between both sexes, with the isotopic values of males being in general more homogenous, higher in $\delta^{15}N$ and lower in $\delta^{13}C$ (Table 18, Fig. 21). There may be two alternative explanations for this trend. The first possibility is the higher consumption of fish by males. However, taking into account the fact that there is only one individual with nitrogen isotopic values higher than 11‰ (JOSH13, Male) and the mean $\Delta^{15}N_{human\text{-}fauna}$ of 2.7-3.1, it seems rather improbable that fish accounted for a substantial part of the diet of GMH males. Alternatively there is a more plausible explanation lying in the lower consumption of animal protein in females together with the relatively higher consumption of millet. Though medieval populations are generally considered to be male-dominant, the higher consumption of animal protein by males is not in any case a uniform pattern in the Middle Ages (Kjellström et al. 2009; Reitsema and Vercellotti 2012). With only one site representing the GM hinterland, we are not able to state if this is a typical feature for the rural part of the Great Moravian population. Potentially this could be caused by the close relation of the inhabitants of Josefov to the near stronghold of Mikulčice. The demographic structure of the Josefov cemetery, with the majority of females (Hanáková and Stloukal 1966) have led some researchers to the hypothesis that Josefov was not a purely agricultural site but that its male population had some specific functions e.g. in the defense of Mikulčice castle (Stloukal and Vyhnánek 1976). Their close relation and potential temporary stays in the rich center may have influenced the quality of their diet.

There was no relation between diet and the number and quality of grave goods (Tables 18 and 19) which corresponds to the simple and homogenous character of grave inventory in this burial site.

TABLE 18. The impact of biological and socio-economic factors on human isotopic values in the Josefov I sample, the results of Mann-Whitney/Kruskal-Wallis test[a]

	N				p		
	Males	**Females**	**ND**		**All**	**Males**	**Females**
Sex	12	20	0	$\delta^{13}C$	**0.039**	-	-
				$\delta^{15}N$	**0.009**	-	-
Age: younger/older than 35	2/10	2/18	0	$\delta^{13}C$	0.805	NS	NS
				$\delta^{15}N$	0.358	NS	NS
Grave goods: A/B/C	1/6//5	9/5/6	0	$\delta^{13}C$	0.438	NS	0.611
				$\delta^{15}N$	0.319	NS	0.780

[a] A = graves with spurs, axes, gold, silver or bronze objects; B = graves with ceramics, glass, Fe and other objects; C = without findings; NS = no statistical analysis was performed do to the low number of individuals in certain groups; significant at <0.05 boldfaced.

TABLE 19. Pairwise comparison of groups according to the socio-economic status in the sample of Josefov I classified according to Unzeitigová (2000)[a]

	All adults		**Males**		**Females**	
	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$
A-B	0.421	0.922	-	-	0.770	0.823
A-C	0.376	0.619	-	-	0.586	1.000
B-C	0.997	0.403	-	-	0.922	0.814

[a]A = graves with spurs, axes, gold, silver or bronze objects; B = graves with ceramics, glass, Fe and other objects; C = without findings.

From the individual values, two males are set apart from the otherwise homogenous group of male isotopic values. JOSH13 shows the highest $\delta^{15}N$ values in the whole sample (11.3‰) together with an extraordinary low $\delta^{13}C$ (-19.8‰). JOSH10 is untypical due to the extraordinarily low $\delta^{15}N$ (7.9‰): the lowest value from the entire Great Moravian sample. However, archaeological data does not offer any explanation for this untypical dietary behavior. Both males were buried without any grave goods and their graves are not in any special location within the graveyard. The skeletons of JOSH10 and JOSH13 do not show any severe skeletal pathology. JOSH13 isotopic values are within the variability of the Mikulčice population so this individual may well have spent a substantial part of his life in the Mikulčice center but, without any supporting arguments, this is only a hypothesis.

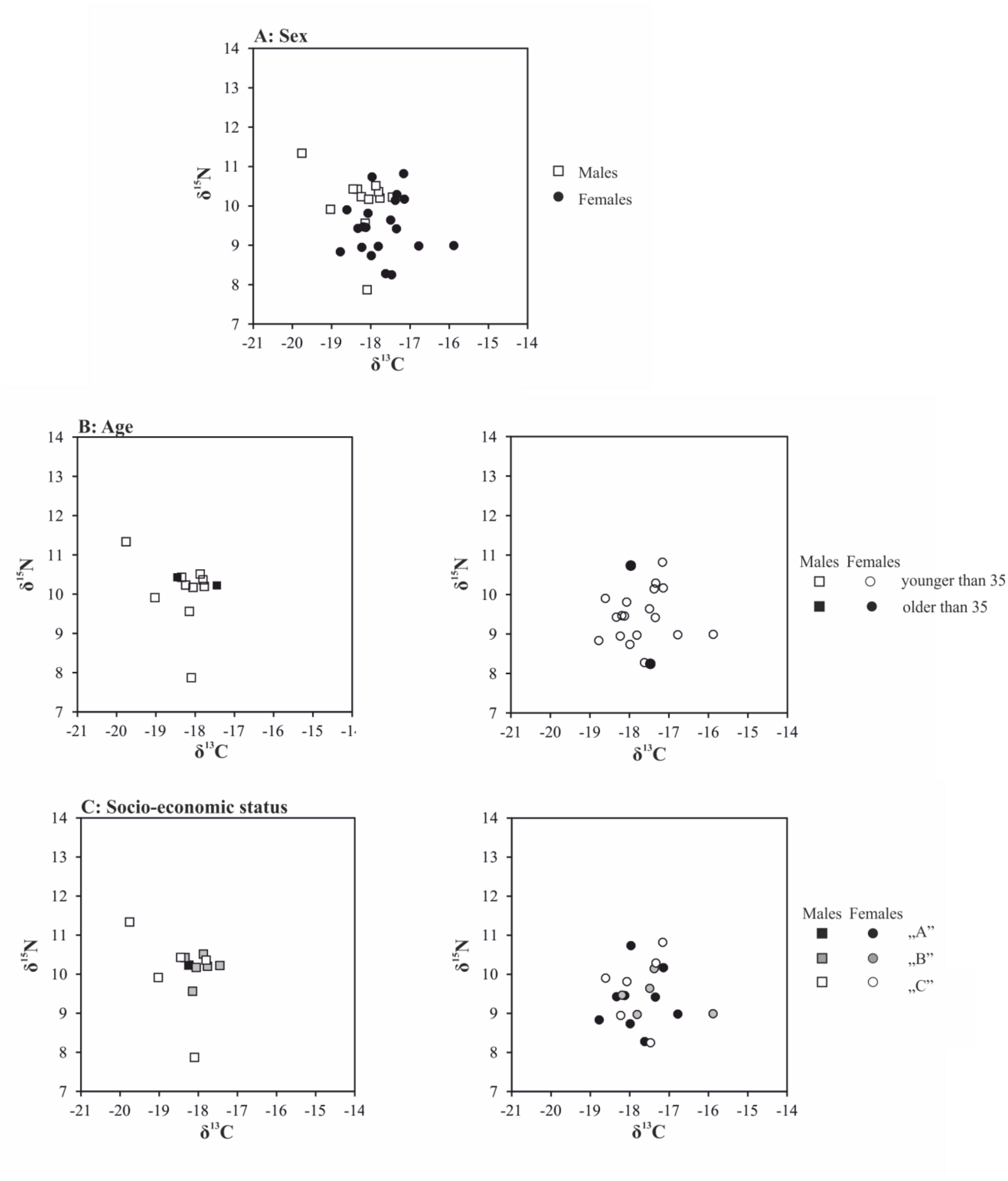


Fig. 21. The relationship between biological and socio-economic factors and human isotopic values in the Josefov sample. A = graves with weapons, gold, silver or bronze objects; B = graves with objects of daily use; C = without grave goods.

7.2.5 Late Hillfort sites (Louky od Břeclavska and Josefov II)

In the case of Josefov, there were no macroscopically observable differences in bone preservation between Great Moravian and late Hillfort graves with all of them appearing dry and porous. Samples from Louky also appeared similar. So generally, bones coming from areas located outside the flood plain appeared more badly preserved than those from the centers. Three individuals from the Josefov II sample showed a slightly higher percentages of both carbon and nitrogen than are the recommended range (DeNiro 1985; van Klinken 1999). However, their C:N values are in accordance with well-preserved collagen and there was no significant correlation between isotopic values and the collagen preservation criteria (Table 20, Fig. 22).So no samples were excluded from the statistical analysis.

TABLE 20. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{13}C$; $\delta^{15}N$) and collagen preservation criteria in the late Hillfort sample

	Yield (%)	**Carbon Content**	**Nitrogen Content**	**C:N**
$\delta^{13}C$	0.878	0.684	0.500	0.814
$\delta^{15}N$	0.269	0.434	0.713	0.294

Due to the low sample sizes from late Hillfort sites and because there was no significant difference in isotopic values between Josefov II and Louky (Table 21), results from both the sites were treated as one combined sample.

TABLE 21. The comparison of isotopic values between the late Hillfort population sample from Josefov II and Louky - the results of Mann-Whitney test

N Josefov	**N Louky**		**Z**	**p**
10	21	**$\delta^{15}N$**	-1.82	0.07
		$\delta^{13}C$	1.50	0.14

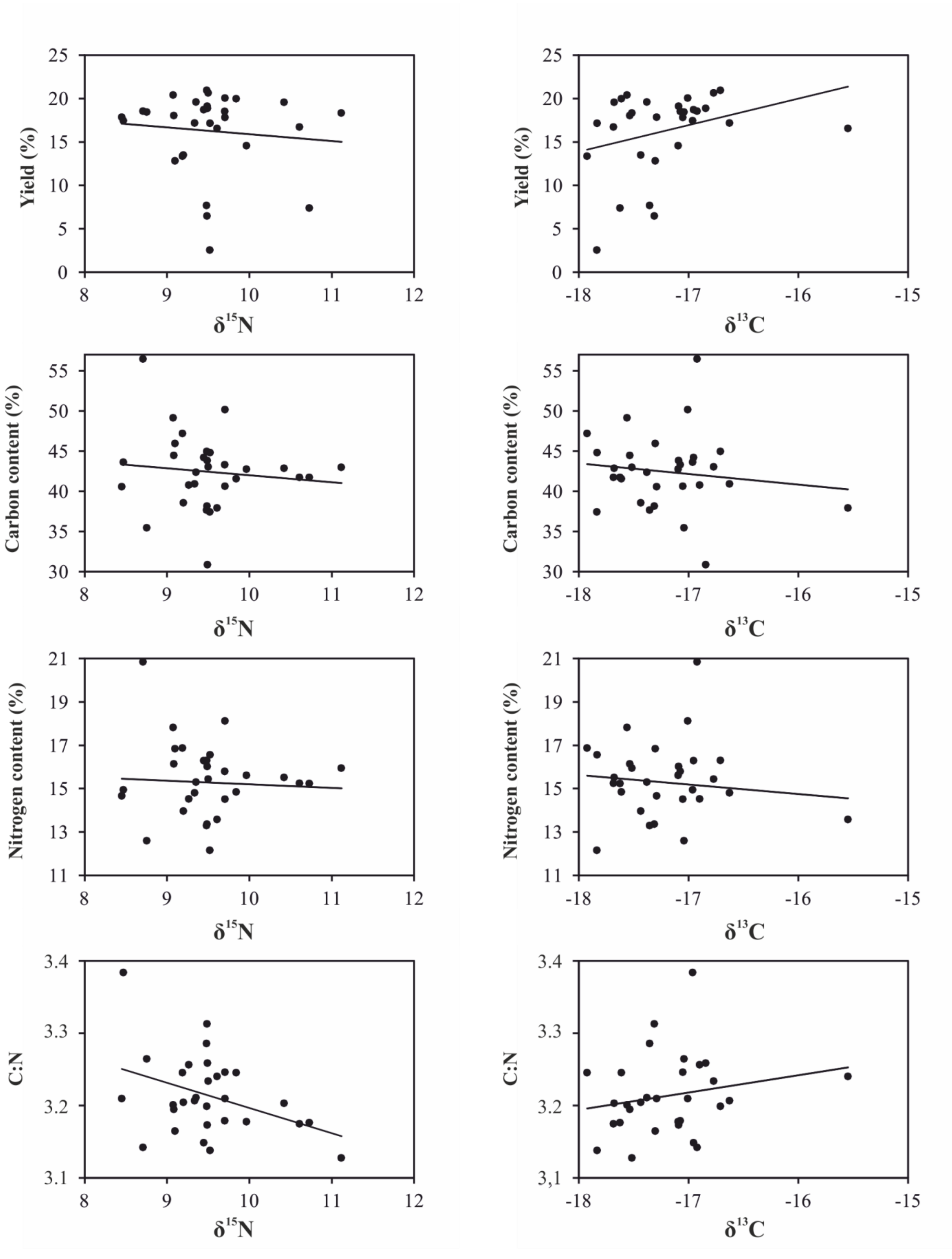


Fig. 22. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in late Hillfort sample.

In this combined sample, carbon isotopic values range from -17.8 to -15.6‰ and $\delta^{15}N$ values range from 8.5 to 11.1‰. More detailed summary data is presented in Table 22.

TABLE 22. Basic statistics of the late Hillfort sample

	All adults		**Males**		**Females**	
	$\delta^{13}C$	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\delta^{13}C$**	**$\delta^{15}N$**
N	31	31	19	19	11	11
Min	-17.8	8.5	-17.8	8.5	-17.2	8.5
1st quartile	-17.6	9.2	-17.6	9.4	-17.5	8.9
Mean	-17.2	9.5	-17.2	9.7	-17.2	9.2
SD	0.5	0.6	0.4	0.6	0.6	0.4
Median	-17.3	9.5	-17.2	9.5	-17.4	9.2
3rd quartile	-17.0	9.7	-17.0	9.8	-17.0	9.5
Max	-15.6	11.1	-16.6	11.1	-15.6	9.8
Human *vs.* fauna (Δ)[a]	3.0-3.3	3.3-5.0[b]	3.0-3.2	3.5-5.2[b]	3.0-3.3	3.0-4.7[b]

[a] mean value of the spacing in isotopic values between human and fauna. As faunal data, the values of the main consumed domesticated species (cattle, sheep/goat, pig) were used; the presented interval comprises differences between species.

[b] the wide interval of $\Delta^{15}N_{human\text{-}fauna}$ is caused by untypically low isotopic values of 2 pigs (discussed in the text).

For the late Hillfort period, the most striking feature is the increase in carbon isotopic values. Because nitrogen isotopic values remain relatively low, the observed isotopic change was most probably caused by the higher consumption of millet. There was a small but statistically significant difference in nitrogen isotopic values ($p=0.045$) but not in carbon isotopic values between both sexes (Table 23, Fig. 23). It may be therefore suggested that millet was consumed in substantial quantities by both males and females. Regrettably, it was not possible to evaluate the potential relation between isotopic values and the age-at-death because the number of late Hillfort individuals younger than 35 years of age was too low for such a comparison. Similarly, it was difficult to investigate the impact of social status because of the uniformity of burial rite regardless of the socio-economic position of the buried individual. In some graves simple inventory, such as temple rings or coins were found, and so we tested for the potential difference between graves with and without any grave goods. However, no significant difference was found between these two groups (Table 23). There were no examples of specific burial rites or skeletons with pathologies or any other remarkable anthropological findings.

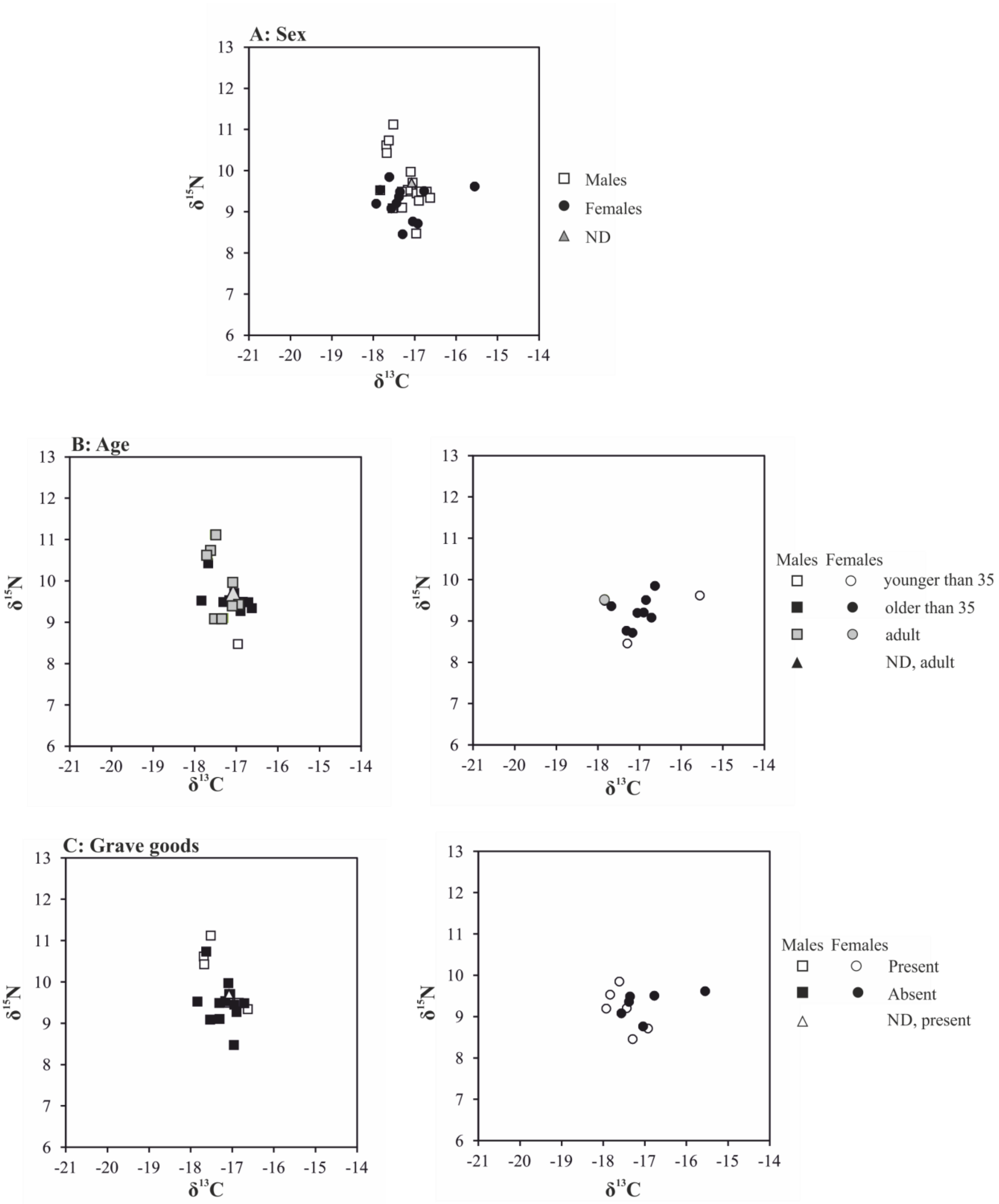


Fig. 23. The relationship between biological and socio-economic factors and human isotopic values in the late Hillfort sample. ND = undetermined sex.

TABLE 23. The impact of biological and socio-economic factors at human isotopic values in the late Hillfort sample, the results of Mann-Whitney test[a]

	N				p		
	Males	**Females**	**ND**		**All**	**Males**	**Females**
Sex	19	11	1	**$\delta^{13}C$**	0.992	-	-
				$\delta^{15}N$	**0.045**	-	-
Age: younger/older than 35	2/9	2/8	-	**$\delta^{13}C$**	NS	NS	NS
				$\delta^{15}N$	NS	NS	NS
Grave goods: presence/absence	7/12	5/6	1/0	**$\delta^{13}C$**	0.775	NS	NS
				$\delta^{15}N$	0.229	NS	NS

[a] NS = no statistical analysis was performed do to the low number of individuals in certain groups; significant at <0.05 boldfaced.

7.2.6 Comparison between sites (intra-population variability and diachronic trends in diet)

The comparison between the studied sites was focused on three main questions. Firstly, was there a difference in diet among inhabitants of one of the most important centers (Mikulčice) and those from a center of a secondary level (Pohansko)? Secondly, was there a difference in diet between inhabitants of Great Moravian centers and those from their hinterland? And finally, was there a diachronic dietary change between the Great Moravian and late Hillfort period? The results of statistical comparison are presented in Table 24 and discussed in separate chapters.

TABLE 24. Isotopic differences between defined groups of the Great Moravian and late Hillfort population: the results of t-test/ Mann-Whitney test/ Kruskal-Wallis test, p-values[a]

	N			$\delta^{13}C$(‰)			$\delta^{15}N$(‰)		
	All	**Males**	**Females**	**All**	**Males**	**Females**	**All**	**Males**	**Females**
MIK *vs*. POH	70/56	34/31	36/24	0.545	0.578	0.062	0.444	0.245	0.886
All[b]	189	101	86	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
GMC *vs*. GMH	70/32	65/12	60/20	0.859	0.546	0.054	**<0.001**	**<0.001**	**<0.001**
GMC *vs*. LH	70/31	65/19	60/11	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
GMH *vs*. LH	32/31	12/19	20/12	**<0.001**	**<0.001**	0.375	0.678	**0.034**	0.791

[a] MIK = Mikulčice; POH = Pohansko; GMC = Great Moravian centers; GMH = Great Moravian hinterland; LH = late Hillfort; significant at <0.05 boldfaced.

[b] the results of Kruskal-Wallis test considering GMC, GMH and LH groups.

7.2.6.1 Diet in Great Moravian centers

Generally, the isotopic values of inhabitants of both Great Moravian centers are characterized by relatively high $\delta^{15}N$ values, suggesting a diet rich in animal protein, and by a high variation in nitrogen isotopic values (Fig. 24). Besides the variable access to animal protein, the observed variability may have been caused or at least amplified by the availability of food items, such as eggs and poultry, which have distinct isotopic values (see chapter 7.1. for details) or by the high quality meat of young animals (lamb and veal) with a persisting breastfeeding signal (Hedges and Reynard 2007). Although fish do not appear to be a staple food source at the population level, we could not exclude their consumption and subsequent influence on isotopic values in some individuals as we discuss later.

Regarding the comparison between the two sampled Great Moravian centers, dietary differences were presumed as a result of several factors: Firstly, there is a clearly different position in the hierarchy of the Great Moravian settlement structure with Mikulčice being one of the main centers of the Great Moravian Empire while Pohansko was probably a secondary center dependent on the principal center of Mikulčice. Secondly, there is a difference in the dating of both sites with the Pohansko sample being more recent – dated mainly to the final phase of the Great Moravian period.

Quite surprisingly, the comparison of isotopic values between these two sites (Table 24, Fig. 24) showed no significant isotopic differences between Mikulčice and Pohansko. This is interesting when taking into account that the cemetery at Pohansko is supposed to have served a much smaller and more closely related group of people. While big cemeteries in Mikulčice "Castle" are supposed to be the place of burial of a broad spectrum of all socio-economic groups of inhabitants, including members of the true Great Moravian elite, Pohansko cemetery is supposed to have served exclusively the family and servants living in the neighbouring magnate's court (Macháček et al. 2014). Additionally, $\delta^{15}N$ values of males show higher variability in Pohansko (see Tables 9 and 13).

Hypothetically this could reflect the development of the social structure of Great Moravian society during the final phase of its existence. At this time archaeological data suggests some relaxation of strict social rules with the emancipation of part of the Great Moravian nobility who tried to imitate the life style of the ruling house by, among other things, the founding of private churches. But apparently not all the members of their households had equal access to high quality foods (namely animal protein).

In Pohansko, we may see one other potential testimony to the disruption of the socio-economic structure and subsequently also to the food redistribution system supplying the GM centers. It is the exceptionally high proportion of hunted fauna (including, for example, many bears or beavers) found at this site (Dresler and Macháček, personal communication).

These new dietary sources may have substituted for the protein from domesticated animals and also contributed to the increased variability of nitrogen isotopic values. This means that inhabitants of centers were most probably able to find alternative sources of foods (such as wild fauna if animal protein was in issue) in reaction to the potential disruption of food redistribution system.

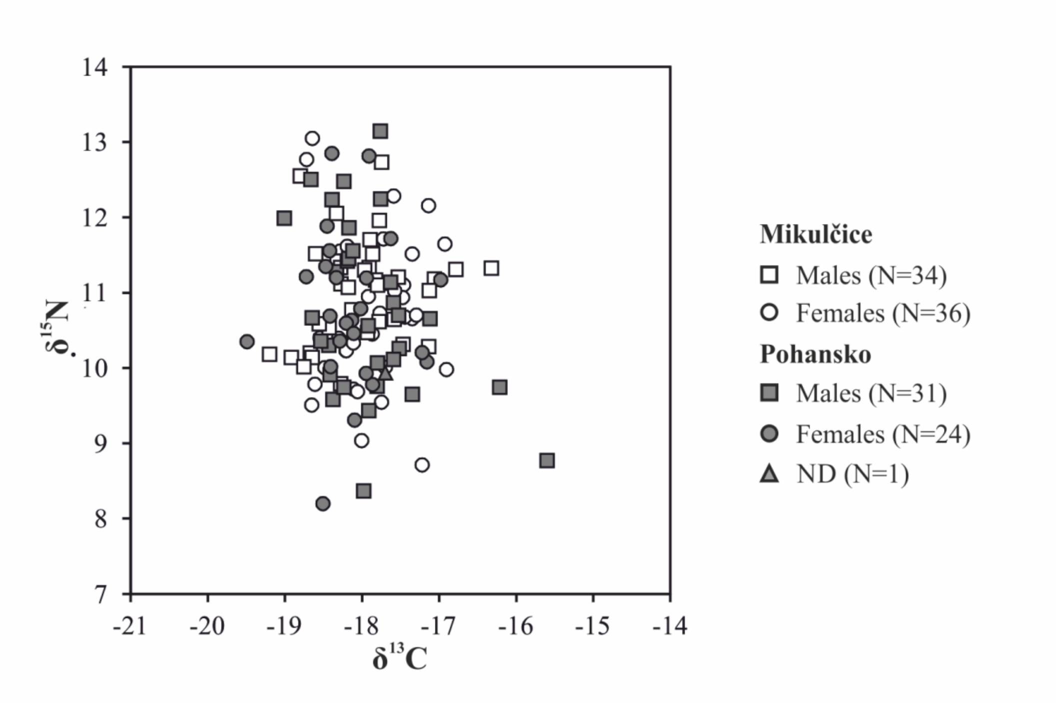


Fig. 24. Comparison of human bone collagen isotopic values between the Great Moravian centers of Mikulčice and Pohansko. ND = undetermined sex.

As stated previously, a common feature for both GM centers was socio-economic status being an important determinant of male diet. Common to both the centers was also the absence of analogical feature in females. As apparent from the detailed view at the data (Fig. 25), the observed pattern slightly differs between both sites. In Mikulčice, the males from well-equipped graves show the high consumption of animal protein as well as a high homogeneity of diet. They do differ in their δ^{15}N from other males ($p=0.033$) but also from females buried with rich grave goods ($p=0.048$). On the other hand, in Pohansko, individuals of both sexes buried in graves with construction share the pattern of a higher proportion of animal protein and lower variability of diet. But it was only in the male sample where the difference was statistically significant (p=0.010).

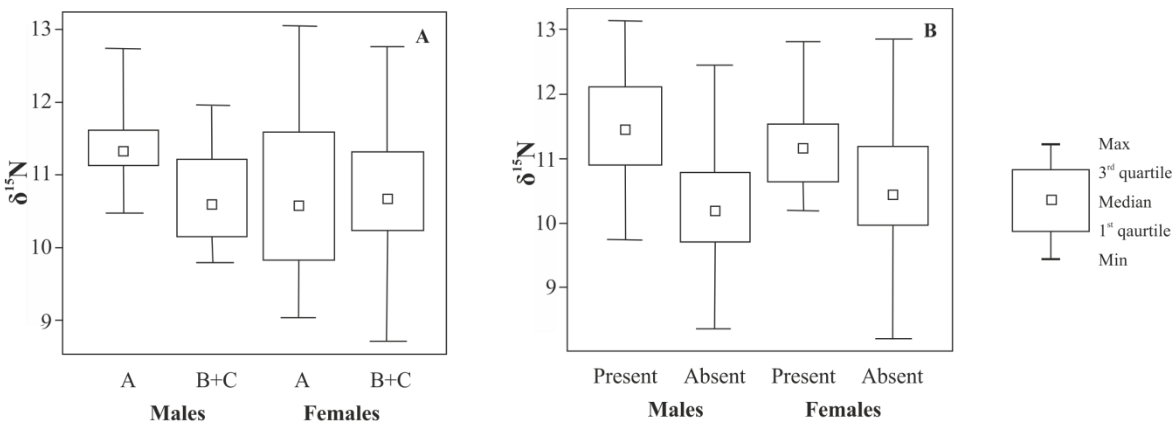


Fig. 25. The relation between nitrogen isotopic data (median, 1st quartile, 3rd quartile, min, max) and indicators of socio-economic status in the Great Moravian centers. A: $\delta^{15}N$ *vs.* the quality of grave goods in the sample of Mikulčice (A = graves with weapons, gold, silver or bronze objects; B = graves with objects of daily use; C = without grave goods). B: $\delta^{15}N$ *vs.* the presence of grave construction in the sample of Pohansko.

Such a dichotomy in dietary behavior, where socio-economic status determines the diet of both sexes in different ways, has already been observed several times in European medieval populations, resulting in two alternative explanations. The first one offers the so-called “cultural buffering theory” according to which one of the sexes is favoured by society, providing males or females with better and more stable living conditions, including preferential access to high quality foods such as animal protein (Reitsema and Vercellotti 2012). Alternatively, such values may be explained by the higher mobility of one sex, from environments with different sources of food, distinct dietary habits or from isotopically different ecosystems (Kjellström et al. 2009). One of the causes for the different migration rate between the sexes may be the tradition of postmarital residence. The patrilocal model of postmarital residence would correspond well with the pattern of the Mikulčice sample. The isotopic data suggests that members of elites may have married females from other noble families coming from more distant areas. However, there was no relation observed between age at death and diet in the potentially migratory group of females buried in well-equipped graves (p=0.300 for carbon and 0.250 for nitrogen) which could be supposed if they had come to Mikulčice after their marriage generally in their youth (but one has to keep in mind that the number of individuals is low). On the other hand, the idea of higher cultural buffering of males from Mikulčice castle has some support in the studies on developmental stress and workload (Bigoni et al. 2013; Havelková et al. 2010). But the weak point of these studies is that they did not divide the castle population into distinct socio-economic groups. In each case, it would be surprising if the male buffering played the most important role in the group with the supposed highest socio-economic status and thus best living conditions in general.

Though the underlying motivations for observed dietary behaviour may remain unclear, it seems that both Mikulčice and Pohansko shared the same pattern in which the more strictly differentiated social roles caused substantial differences in life styles and diets within the male part of the population.

Another interesting dietary feature common for the two Great Moravian centers should be mentioned here. It refers to the small group of individuals buried in the church interiors. As stated previously, one male from Mikulčice and two from Pohansko shared a diet characterized by relatively high $\delta^{15}N$ and low $\delta^{13}C$ values. This may suggest a diet rich in animal protein and low in millet. But since socio-economically motivated differences in millet consumption at the population level were not discovered, perhaps a more plausible explanation of this trend may lie in the consumption of some quantity of fish.

The higher consumption of fish, above the norm of the general populace, was often observed in members of the medieval clergy to whom the stricter obedience of Christian fast rules was imposed (Barrett and Richards 2004; Müldner et al. 2009; Salamon et al. 2008). In the Great Moravian context some of the grave places in church interiors may have well belonged to local priests. However, archaeological evidence is at odds with this interpretation: the male from Mikulčice 2nd church was buried with a sword which indicates that he came rather from the lay elite. Also in Pohansko, the prestigious position of one of the graves on the main church axis indicates the grave of a founder of the church, coming from the rank of the Great Moravian nobility (Macháček et al. 2014; Poláček 2008b). Although the small sample size precludes any statistical analysis, these results may suggest that people honoured by exclusive resting place in the church premises shared dietary habits, which may be explained by stricter abidance to Christian rules. More individuals from the church interiors should be sampled in the future in order to further support this hypothesis.

7.2.6.2 Great Moravian centers *vs.* hinterland (urban-rural differences.)

At first glance, (Fig. 26), the diets of inhabitants of the Great Moravian hinterland do differ from the population of centers. Statistical analysis showed a significant difference in $\delta^{15}N$ values (Table 24). Carbon isotopic values of both samples do not differ substantially, although in females the result is close to the level of statistical significance. This means that the main difference between both sub-samples lies undoubtedly in the higher consumption of animal protein in the populations of centers. Although the diet in centers may appear to be more variable in its proportion of animal protein, the difference in variability of nitrogen isotopic values was not statistically significant (p=0.599 for the combined sample of both sexes). Millet was consumed in a similar amount, most probably in the form of porridge, in both center and hinterland environments and across all the socio-economic groups. The group of hinterland females appears to be slightly specific in the consumption of millet, differing substantially in their carbon isotopic values from GMH males and being close to the level of statistical significance when compared to GMC females.

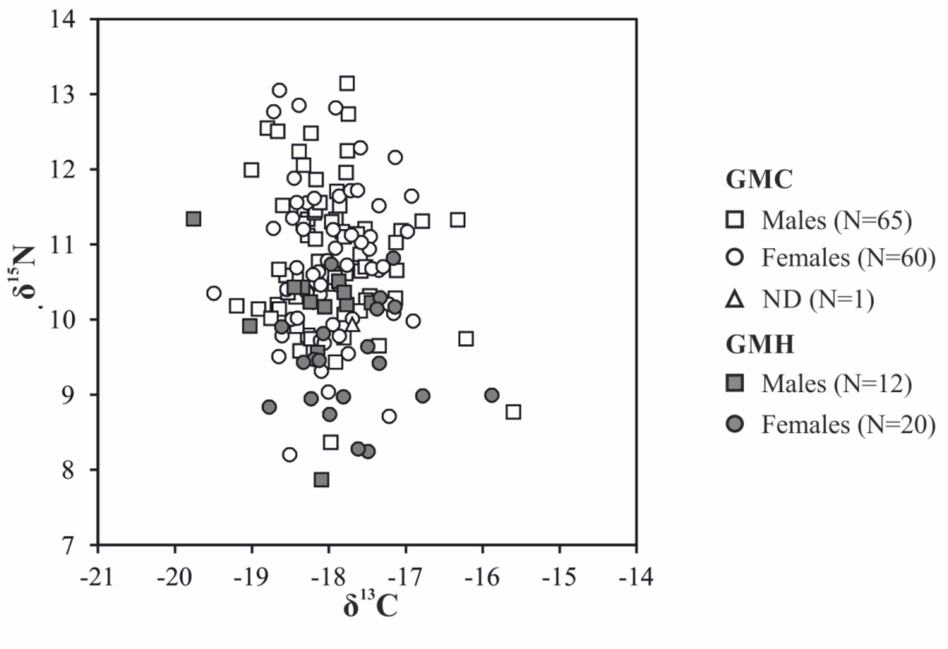


Fig. 26. Comparison of human bone collagen isotopic values between the Great Moravian centers (GMC) and hinterland (GMH). ND = undetermined sex.

This feature may be caused (or at least augmented) by the low proportion of animal protein in their diet. GMH females are the group with the lowest mean nitrogen isotopic values from all the sub-groups of the Great Moravian population. If plant foods represented a substantial source of their dietary protein, the millet consumption may have been more visible in their isotopic signal. The absence of a systemic and significant difference in carbon isotopic values between both population groups indicates that there was no significant difference in the consumption of fish. This is quite surprising with respect to the natural conditions as well as the supposed religious pressures acting in urban centers. However, as shown by the previous isotopic studies, a location offering the availability of fish did not implicitly lead people to a significant use of aquatic resources (Barrett et al. 2004; Barrett and Richards 2004; Eriksson et al. 2008; Le Bras-Goude et al. 2013; Papathanasiou 2003; Petroutsa and Manolis 2010). On the second point, our information of the fasting prescription imposed on Great Moravians (or more generally on early Christianized populations of the 9th century) by the church are very limited. The only written note comes from the contemporary document *The Responses of Pope Nicholas I to the Questions of the Bulgars* (dated 866), which prescribes the abstinence from meat for a substantial part of the year. Meat was prohibited during Lent, before Pentecost, Assumption of Mary and Christmas, as well as on all Fridays and all the vigils of famous Christian feasts (Bartoňková et al. 1971). However this source does not include the information of whether fish was allowed as a fasting dish or not. Usually fish was accepted by the Church during fasting, but exceptions from this practice may be found (Gregoricka and Sheridan 2013). In each case, our data does not show any indication of the substantial influence of Christianity on the diet at population level.

Also the testimony of other isotopic studies suggests that the attitude of people to the religiously motivated dietary prescriptions differed among sites and populations. Usually the phenomenon of increased fish consumption after 1000 AD observed across most of medieval Europe (Barrett et al. 2004; Müldner and Richards 2007; Salamon et al. 2008) is linked to the increased pressure to abide by the fasting rules. The influence of Christianity before 1000 AD is much more ambiguous. A shift to the increased use of aquatic resources was documented even in Rome's early Christians from the 3rd-5th century AD (Rutgers et al. 2009) as well in the first generation Christian converts in the Scottish Viking age site of Newark Bay (Barrett and Richards 2004). On the other hand, even during the 7th century, when Church authority is supposed to have been already well established in the studied area, the Italian sample from the site Castro dei Volsci did not show the substantial consumption of fish common in later periods (Salamon et al. 2008).

To conclude this part, the comparison of diet between centers and hinterland together with socio-economic differences in diet found in the population of centers, reflects a clear inequality in the access to the dietary resources, which suggests an advanced socio-economic stratification of the society. On the other hand, we found no indication of dietary habits which could be linked to different religious behaviour at the population level. Also, our results contrast with historical resources, which suggest a socio-economical gradient in the consumption of millet. According to our data, millet was neither the diet of the poor (Adamson 2004), nor the favored dish of the rich, as suggested by Beranová (2005) but was consumed across all socio-economic groups and in both an urban and rural context.

7.2.6.3 Late Hillfort sample and the diachronic trends in diet

Although a small sample size, it was possible to observe a substantial shift in dietary behavior in comparison to the Great Moravian period. The pairwise comparison (Table 24) revealed that $\delta^{13}C$ values of the combined sample of both sexes differs significantly from Great Moravian samples of both the centers and hinterland while $\delta^{15}N$ differs from GM centers but is similar to the population of GM hinterlands (Fig. 27). However again, when looking at each sex separately, the observed pattern differs: In males, beside the increased consumption of millet we observe also a significant decline in animal protein consumption when compared to GMH males. During the 11th century, the diet of males became more similar to those of females in terms of both carbon and nitrogen, although for nitrogen a small but significant ($p=0.045$) difference persists. In females, diachronic changes in diet were much less pronounced with the animal protein consumption comparable to the GM hinterland sample. Although carbon isotopic values were increased in females as well, the difference was significant only when comparing LH females to the female population of GM centers, but not GM hinterlands.

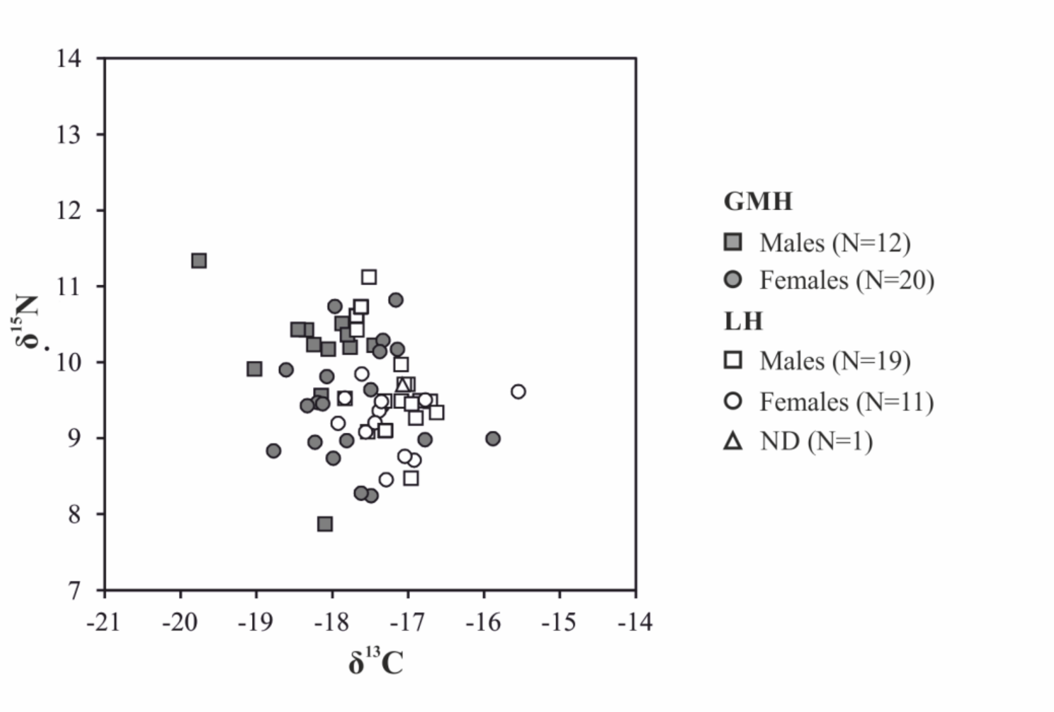


Fig. 27. Comparison of human bone collagen isotopic values between the Great Moravian hinterland (GMH) and late Hillfort (LH) samples. ND = undetermined sex.

As discussed in Chapter 7.1 it is not possible to exclude the possibility that the lower nitrogen isotopic values in the late Hillfort samples may have been caused by the lower values of consumed animals (especially pigs; see Chapter 7.1 for more details). But if this was the true cause, the same decrease should be observed in both sexes, so it appears much more probable that the observed diachronic changes of isotopic values really result from dietary differences.

When discussing the potential causes of the observed phenomenon, both the climatic and socio-economic sphere should be taken into account. Firstly, there is well-documented climatic change (Svoboda et al. 2003), which may have had an impact on agricultural practices. The culminant climatic optimum of the 11th century may have been a most suitable period for the cultivation of millet, which is a warm-requiring and dry-resistant plant (Konvalina et al. 2007; Moudrý 2005; Svoboda et al. 2003). But causes for the observed diachronic changes seem to be more complex. For example the production of wheat, which should also have prospered well in the climatic conditions of the 11th century, declined substantially at that time (Dreslerová et al. 2013), which may suggest the role of factors from the socio-economic sphere. During the 11th century Moravian society clearly regenerated after a period of collapse and instability which followed the fall of the

Great Moravian Empire (Hladík 2014; Macháček and Videman 2013). But according to our data, the quality of the Moravian diet, at least in terms of animal protein consumption, did not reach the levels of the Great Moravian period. The diet of LH males was poorer in animal protein than that of peasants from the Great Moravian hinterland and more similar to that of females. This observation is in accordance with the trend observed already in the GM period of the diet of males being the more sensitive indicator of socio-economic conditions. Alternatively, the observed pattern may represent further evidence of the important role of large proto-urban centers in the lives of males living in their hinterland, as already discussed in Chapter 7.2.6.2. Regrettably, this interpretation is limited due to the above described change in burial rite which has disallowed the estimation of the socio-economic status of the particular individuals.

In each case, the increased consumption of millet may well reflect the changed socio-economic structure of the population, which may have oriented the core of agricultural production to less luxurious, but more stable, crops.

Even in the wider Central European context (Table 7), carbon isotopic data of LH sample are really outstanding. With the mean carbon isotopic value of -17.2‰ and the mean human-faunal carbon isotopic offset of 3.0-3.3, the importance of millet in the 11th century Moravia seems to be higher than in any other comparative population sample.

7.2.7 Apatite results

As stressed previously, this study is primarily focused on the isotopic analysis of bone collagen. Nonetheless, in the small sub-sample of 30 individuals, the carbon isotopic values of bone apatite were also measured to explore the potential utility of this type of analysis in the medieval context of Central Europe. This sub-sample consisted of 10 individuals from Mikulčice, 10 individuals from Josefov and 10 individuals from Louky od Břeclavska. For Mikulčice and Josefov, samples were chosen based on the carbon isotopic values of their collagen samples. The aim was to further analyze preferentially the individuals with outstanding carbon values suggesting the lowest (Group 1) and highest (Group 2) consumption of millet in the whole sample. Additionally, all the individuals from Louky od Břeclavska were included as a representative sub-sample from the late Hillfort period, where the higher millet consumption was suggested based on the collagen results. We have not performed any analyses on the apatite preservation, but since collagen quality indicators met the criteria for good collagen preservation in all the cases, overall good sample preservation was supposed (for discussion on this topic see Chapter 3).

Complete results are presented in Figures 28 and 29 and Table A4. Although a statistically significant positive correlation exists between $\delta^{13}C_{coll}$ and $\delta^{13}C_{ap}$, (Kendall tau = 0.604) higher variability of $\delta^{13}C_{ap}$ values suggest that the sources of energy were more variable in the proportion of C_4 plants than were the protein sources.

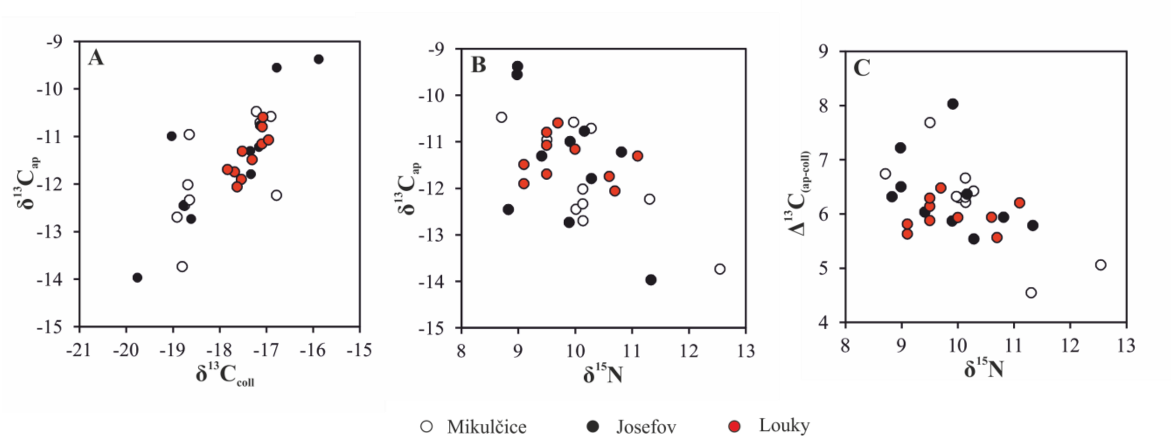


Fig. 28. Complete bone apatite isotopic values in relation to the bone collagen isotopic values. A: $\delta^{13}C_{ap}$ *vs.* $\delta^{13}C_{coll}$; B: $\delta^{13}C_{ap}$ *vs.* $\delta^{15}N$; C: $\Delta^{13}C_{(ap\text{-}coll)}$ *vs.* $\delta^{15}N$.

As discussed in Chapter 3, $\Delta^{13}C_{(ap\text{-}coll)}$ may be used as an indicator of trophic position. $\Delta^{13}C_{(ap\text{-}coll)}$ ratios of individuals with a more carnivorous diet are smaller, because these gain more energy from isotopically depleted lipids. However, this may be applied only in purely C_3 or purely C_4 based ecosystems where dietary macronutrients do not differ isotopically. Apparently this condition is not met in the Great Moravian population due to the clear presence of a millet signal. Although visually there appeared to be a weak negative correlation between $\delta^{15}N$ and $\delta^{13}C_{ap}$ respective to $\delta^{15}N$ and $\Delta^{13}C_{(ap\text{-}coll)}$, these correlations were not statistically significant (Kendall tau = -0.030 respective -0.132). And finally any sign of this type of correlation vanishes in the late Hillfort sample. This is in accordance with the results on bone collagen, which indicate an increase in direct consumption of millet in the 11th century. Thus $\delta^{13}C$ values of protein and energy sources differed more substantially in these samples.

As the next step the model by Kellner and Schoeninger (2007) was applied to our data (Fig. 29).

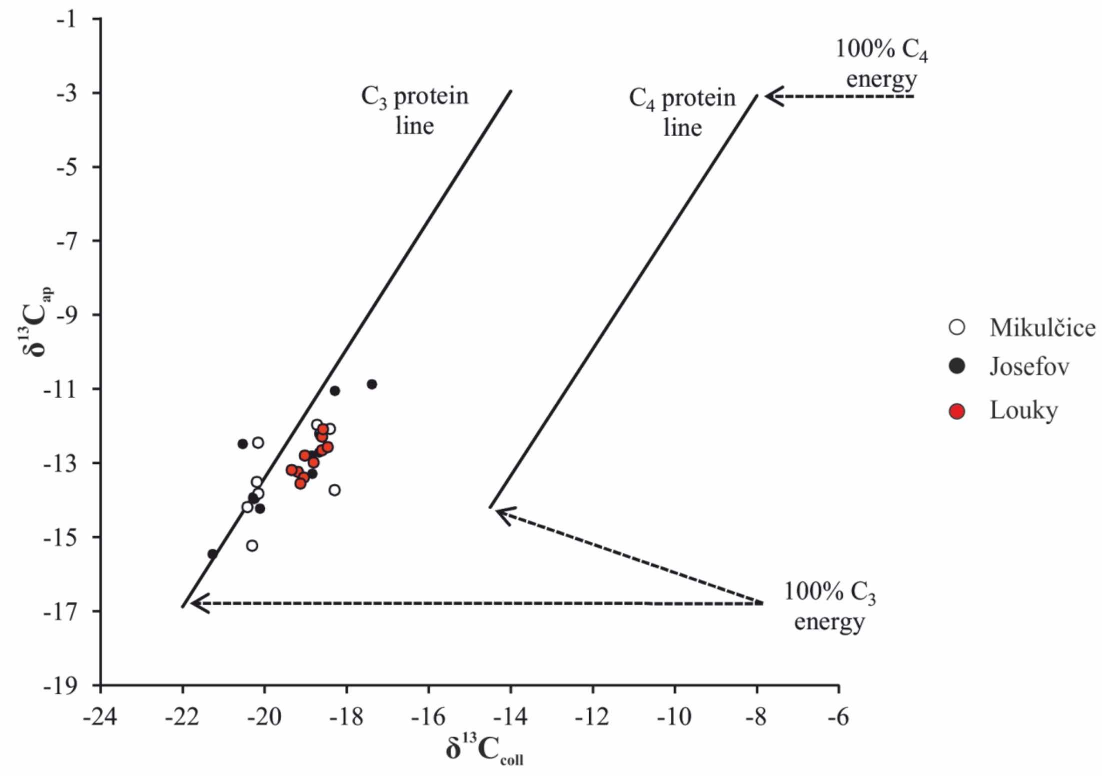
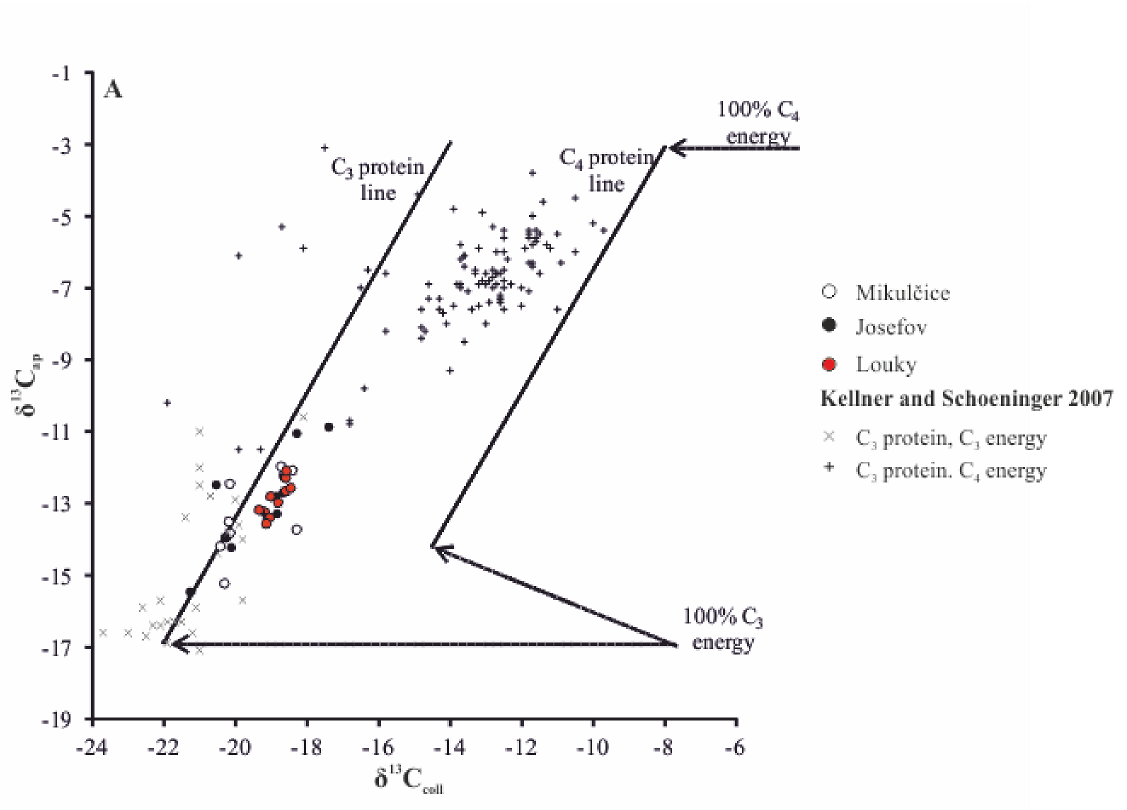


Fig. 29. The position of Great Moravian and late Hillfort individuals in the plot according to Kellner and Schoeninger (2007).

After adjusting the isotopic values for the "Suess effect", all the individuals are located close to the C_3 protein line, suggesting a minimal input of C_4 protein sources and minor input of C_4 energy sources into the diet of Group 1. For Group 2 and the late Hillfort sample, data indicates a higher input of C_4 derived energy and a certain minor input of C_4 protein. This is again in accordance with our results on bone collagen suggesting the direct consumption of millet as a C_4 energy source together with meat and milk from animals foddered by C_3 plants.

When compared with original data by Kellner and Schoeninger (2007) GM Group 1 showed isotopic values within the variability of pure C_3 consumers. GM Group 2 and the late Hillfort sample is located on the border between both C_3protein/C_3energy and C_3protein/C_4 energy consumers, although their values are still closer to C_3 eaters (Fig. 30). This is however not surprising because millet has never been of such importance on the European continent as maize in some of the Native American populations. Much more interesting is the comparison with other European medieval populations (Fig. 30): From the sites explored by Reitsema (2012b), the 11th century site of Kaldus shows a similar range of values as the Great Moravian sample. All the more recent sites cluster more closely to the C_3 protein line and show a lower proportion of C_4 derived energy. Another Polish sample from 11th to 12th century Giecz (Reitsema et al. 2010) is located in between the GM1 group and GM2/LH group. From other sites used for comparison in this study, only the early medieval sample from Voders (Austria) has been analyzed for apatite values. Isotopic values of this sample show low collagen and apatite carbon isotopic values reflecting the predominantly C_3 based ecosystem (McGlynn 2007). Isotopic values of the samples from the Moravian late Hillfort period remain unique even in this wider frame due to their homogeneity (though the small sample size may weaken this finding) and the high proportion of C_4 plants as the sources of energy.

To summarize this chapter briefly, although a small sample size, our results confirm all the findings based on the analysis of bone collagen: They suggest the direct consumption of millet to be of varying importance during the Great Moravian period with an increase in the importance of millet during the late Hillfort period. The late Hillfort period in Moravia appears to be really extraordinary in the importance of millet at least in the context of the Central European Middle ages, although in comparison with some of the New World populations the input of C_4 derived energy was still minor. On the other hand, no substantial new information was gained from the isotopic analysis of bone apatite. That is why the sample size remained limited to 30 individuals.



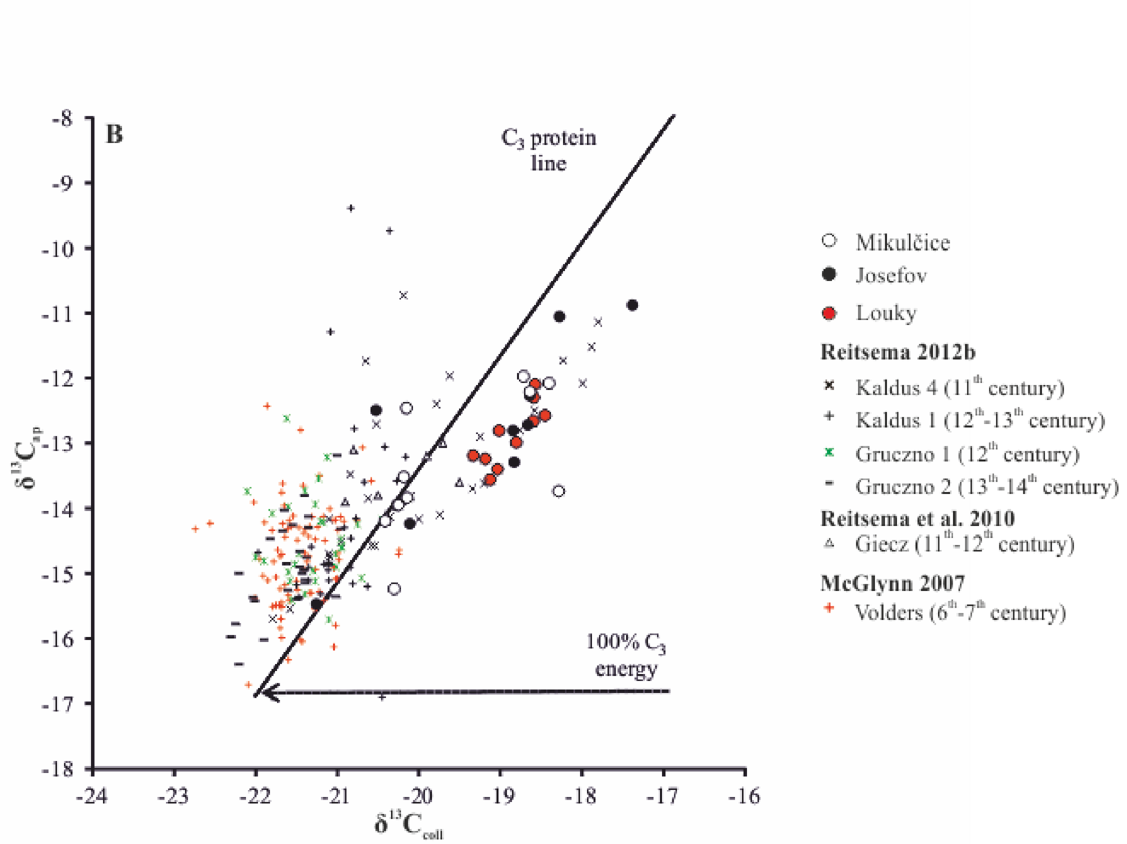


Fig. 30. $\delta^{13}C_{ap}$ and $\delta^{13}C_{coll}$ of Great Moravian and late Hillfort samples in comparison with: A: original data by Kellner and Schoeninger (2007) for population groups consuming C_3 protein and C_3 energy sources / C_3 protein and C_4 energy sources; B: other Central European medieval sites.

7.3 Isotopic data of sub-adults

Complete isotopic data of sub-adults are presented in Table A5. A feeding status of each child was estimated using the $\Delta^{15}N_{t-b}$ values. In accordance with the original paper by Herrscher (2003), $\Delta^{15}N_{t-b}$ value of 0.4‰ was chosen as a threshold for significant dietary change. This value is considered adequate in the light of the measurement precision, as well as the stochastic isotopic variation, reported by other studies (0.3‰) (Chisholm 1989; Katzenberg and Lovell 1999). When $\Delta^{15}N_{t-b}$ value was higher than 0.4‰ the concerned child was regarded as "breastfed," and analogically, when lower than -0.4‰, the child was suggested to be "weaned."

7.3.1 Mikulčice

7.3.1.1 Sample preservation

Visually, the majority of Mikulčice mandibles were compact and difficult to crush. On the other hand, tooth roots in the Mikulčice sample were often very thin and broke easily during the extraction of teeth.

All the samples met the criteria for good collagen preservation (DeNiro 1985; van Klinken 1999). Moreover, there was no significant correlation between isotopic values and the indicators of collagen preservation (Table 25, Fig. 31).

TABLE 25. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{13}C$, $\delta^{15}N$) and collagen preservation criteria in sub-adult human sample from Mikulčice

		Yield (%)	**Carbon Content**	**Nitrogen Content**	**C:N**
Tooth	**$\delta^{13}C$**	0.391	0.690	0.818	0.601
	$\delta^{15}N$	0.914	0.132	0.144	0.072
Bone	**$\delta^{13}C$**	0.510	0.322	0.393	0.438
	$\delta^{15}N$	0.091	0.145	0.112	0.227

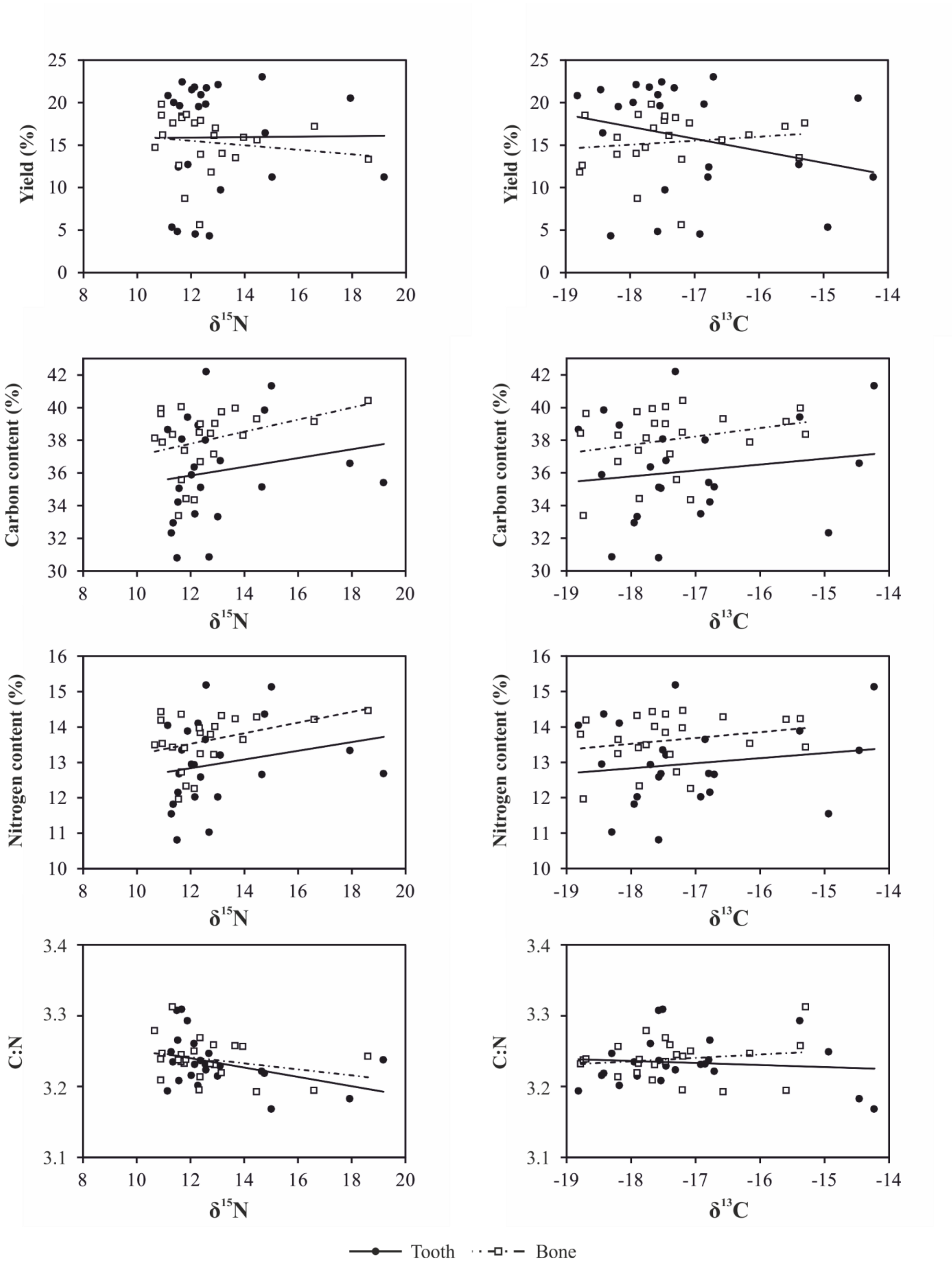


Fig. 31. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in tooth and bone samples of Mikulčice sub-adult sample.

7.3.1.2 Weaning pattern in Mikulčice sample (nitrogen isotopic data)

In the Mikulčice sample, 14 cases of a total number of 23 individuals (Table A5) showed sufficient isotopic variation between tooth and bone samples to estimate the feeding status. These results reveal a great variability suggesting that multiple infant feeding strategies were applied within the Mikulčice population. While the youngest children were weaned during their second year of life, some others may have still been consuming breast milk substantially at the age of four (Fig. 32).

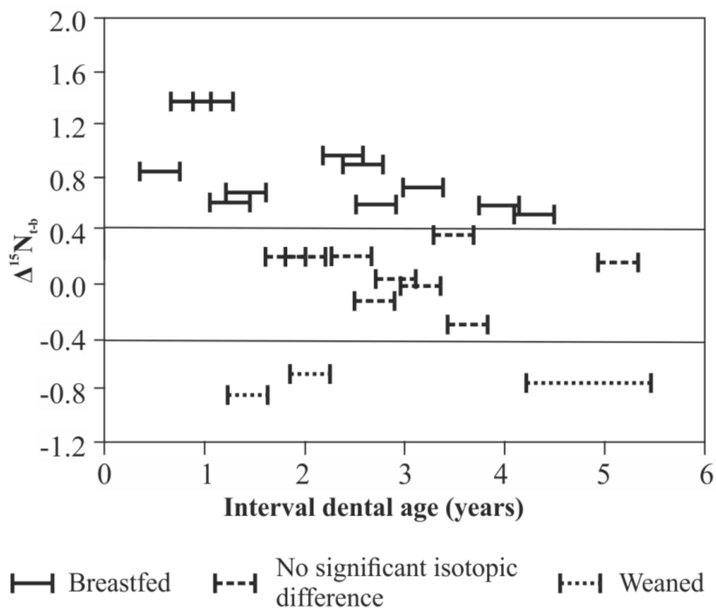


Fig. 32. Suggested feeding status of Mikulčice children based on relative differences between the tooth dentin and bone samples ($\Delta^{15}N_{t-b}$).

These cases of a prolonged period of substantial consumption of breast milk are in fact not so surprising as they appear at first glance. Examples of prolonged breastfeeding beyond the third or fourth year of life may be found in both archaeological (Herrscher 2003; 2005; Waters-Rist et al. 2011) and modern (Moffat 2001; Sellen 2001; Simondon et al. 2001) populations. In some cases, the age at complete cessation of breastfeeding was reported to be more than 6 years (Dettwyler 2004). Also historical sources mention examples of populations where the recommended age of weaning was as high as 3 or even 6 years old (Fildes 1995).

As observed in adults, infant and young child nutrition may also be influenced by the socio-economic status. Regrettably, the number of individuals was too low to perform any statistical analysis of feeding status with regard to social position. However, it remains a fact that both of the individuals who were still breastfed until age 4–5 were buried with outstanding grave goods including “warrior” equipment (spurs) and gold jewelry and thus are believed to be of high socio-economic status. By contrast, the children that were weaned before the age of 2 were buried without any grave goods. However, the impact of the age factor on the quality of grave goods must be taken into account, because the presence, number and luxury of grave goods correlate with the age at death (Stloukal 1970). In other words: the younger the individual the higher the probability that he or she was buried with poor grave goods (or without any at all) regardless of their actual position on the socio-economic scale.

7.3.2 Josefov

7.3.2.1 Sample preservation

Macroscopically, the mandibular bone preservation of Josefov samples were worse than in the case of Mikulčice with a majority of the samples being porous and chalky. For teeth there was no analogical pattern. On the contrary, the tooth roots of Josefov sub-adults were macroscopically in better condition than in Mikulčice.

As in the case of Mikulčice, all the samples met the criteria for good collagen preservation (DeNiro 1985; van Klinken 1999). A statistically significant correlation was found between carbon and nitrogen isotopic values and the carbon and nitrogen content of bone samples (Table 26). However, there are not any clear outliers significantly affecting the correlation (Fig. 33). For this reason, no samples were excluded from the further analysis.

TABLE 26. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{13}C$, $\delta^{15}N$) and collagen preservation criteria in sub-adult human sample from Josefov

		Yield (%)	**Carbon Content**	**Nitrogen Content**	**C:N**
Tooth	**$\delta^{13}C$**	0.541	0.570	0.769	0.895
	$\delta^{15}N$	0.124	0.773	0.935	0.335
Bone	**$\delta^{13}C$**	0.766	**0.004**	**0.003**	0.890
	$\delta^{15}N$	0.179	**0.013**	**0.015**	0.171

[a] significant at <0.05 boldfaced.

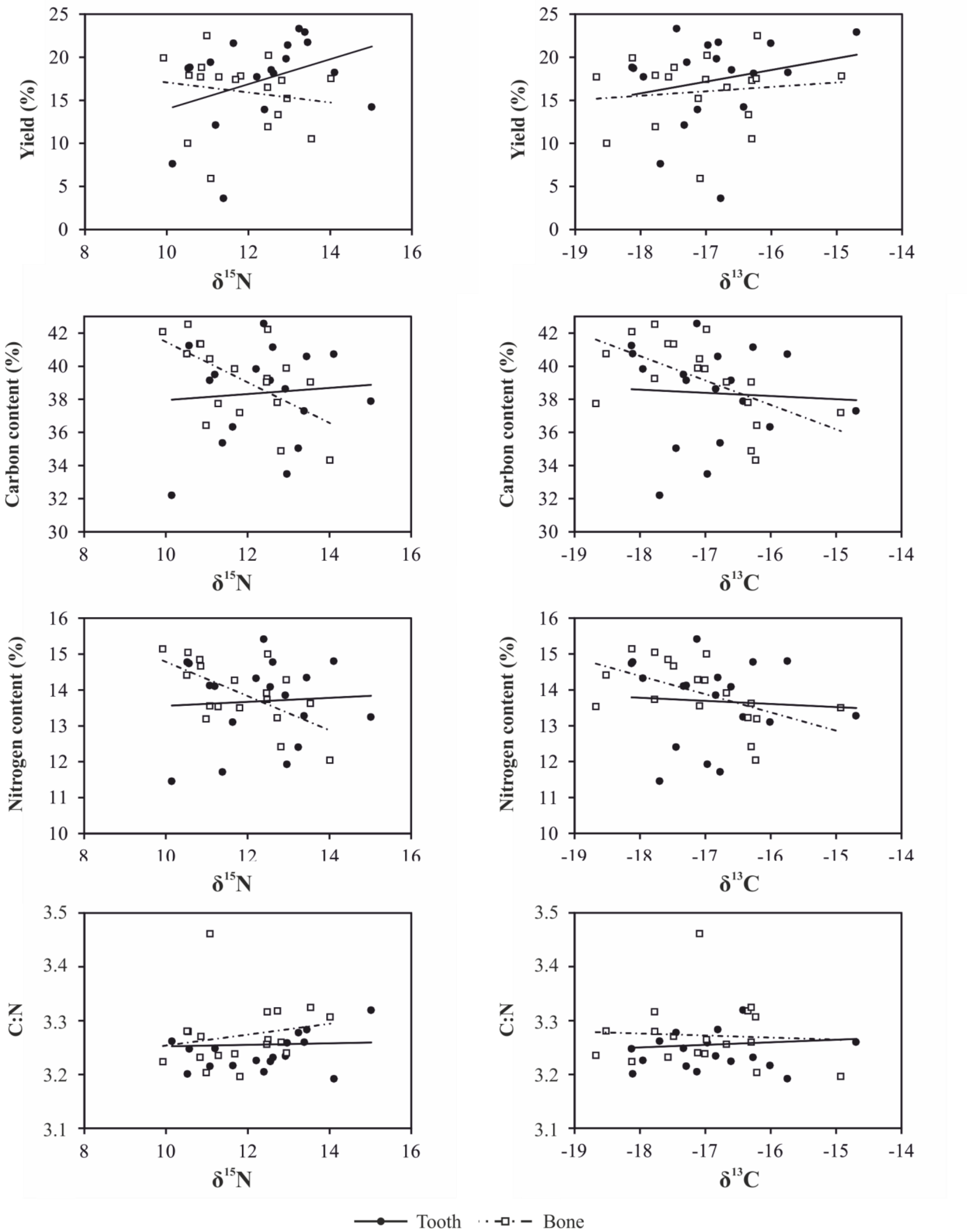


Fig. 33. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in tooth and bone samples of Josefov sub-adult sample.

7.3.2.2 Weaning pattern in Josefov sample (nitrogen isotopic data)

Based on the criteria described earlier ($\Delta^{15}N_{t\text{-}b} > \pm 0.4$), the feeding status was estimated in 11 cases of a total number of 18 individuals (Table A5).

For this hinterland population sample, our data suggest a higher consistency in feeding practices. With two exceptions (JOSS04 and JOSS13, with no significant isotopic variation) all children under 2 years (using the median dental age) had a $\Delta^{15}N_{t\text{-}b}$ value higher than 0.4‰, and were therefore suggested to be substantially breastfed (Fig. 34). During the 3rd year of life a strong decrease in the $\Delta^{15}N_{t\text{-}b}$ value was observed. The youngest children were weaned at this age, while some others were still consuming a substantial proportion of breast milk. Regrettably, a low number of individuals aged between 3 and 5 years were present at the Josefov burial site. The only two individuals representing this age group showed an insignificant isotopic variation. Therefore we were not able to distinguish when exactly the process of weaning was completed among this rural community. However, our data clearly suggests a unique strategy for weaning was applied in Josefov, beginning around or after the age of 2 and being completed probably during the 4th year of life.

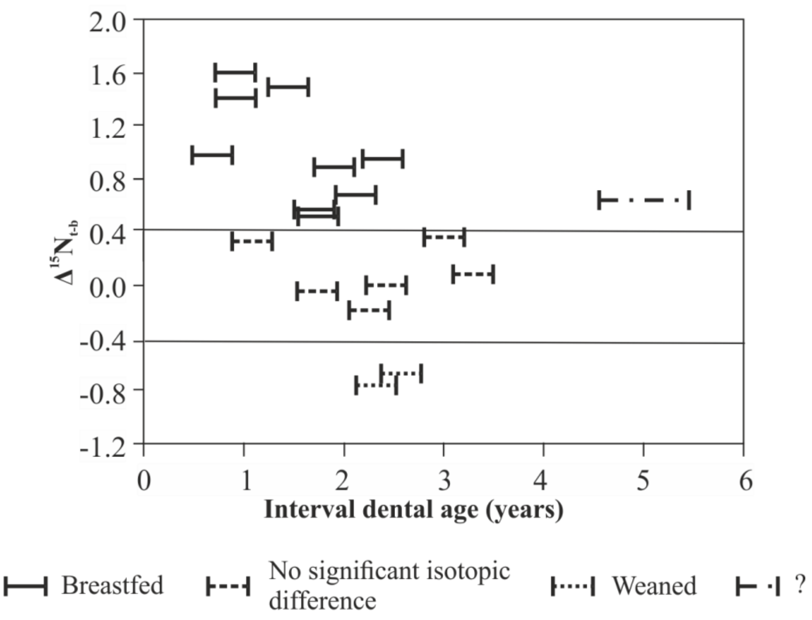


Fig. 34. Suggested feeding status of Josefov children based on relative differences between the tooth dentin and bone samples ($\Delta^{15}N_{t\text{-}b}$).

The only exception from this trend is represented by the oldest individual from the entire sample (JOSS20, aged 4.8–5.6 years). The isotopic values of this individual correspond to a diet substantially based on breast milk. This is, however, highly unlikely taking into account the age of JOSS20 as well as the fact that its $\delta^{15}N$ value was one of the lowest in the whole sample (the lowest in bone). Potential causes of these unexpected isotopic values will be discussed later. For the statistical analysis this outlier was excluded from the sample.

The Josefov sample shows no evidence of any relationship between infant diet and social status.

7.3.3 Intra-population variability in feeding practices

We have evaluated the relationship between the breastfed/weaned status and the type of residency (center *vs.* hinterland) by using multiple logistic regression analysis, which enables adjustment for the age (Table 27). Our data shows no significant relationship between the breastfed/weaned status and residency (p=0.902). These results suggest that there were no norms for the optimal duration of breastfeeding applied specifically in the center or hinterland part of the population. However, the higher variability of weaning behavior observed in the Mikulčice sample (though not possible to confirm statistically) remains a phenomenon deserving wider discussion.

TABLE 27. Factors associated with the weaned status (vs. breastfed status): simple and multiple logistic regressions[a]

Explanatory variables		**N**	**p Wald**	**p (interaction)**[a]
Type of residency	**Mikulčice**	14	0.902	0.284
	Josefov	11		
Age, (continuous)		25	0.211	

[a] p Wald of the interaction age* type of residency.

The greater diversity in the duration of breastfeeding observed in the Mikulčice sample may be due to several potential causes. The first potential factor lies in the higher influence of Christian rules and taboos. As previously suggested (see Chapters 1 and 2), Christianity is supposed to have spread earlier and more quickly among the populations of centers. Thus pressure to abide by Christian prescriptions could be higher in centers in comparison with the rural areas. For the 9th century, we do not know any recommendations for the duration of breastfeeding (Bartoňková et al., 1971). If there were any rules postulated by the Great Moravian church they remain completely unknown to us. However certain rules concerning family life and child care probably existed (Thorvaldsen 2008). As a unique example, the document *The Responses of Pope Nicholas I to the Questions of the Bulgars* recommends sexual abstinence during the entire period of breastfeeding (Bartoňková et al. 1971). The real impact of these recommendations is however impossible to estimate: It seems that Christianity influenced certain aspects of the lives of Moravians (e.g. burial practices as reflected by the decrease in the number and quality of grave goods), while others spheres of their lives (perhaps more personal and so more difficult to control) such as dietary behavior of adults (or at least the part which may be observed by isotopic analysis) remained unchanged despite the clear recommendations. The new prescriptions clearly could lead at least some women in Mikulčice to the abandonment of the established norm when the weaning of their children was at issue but to estimate the strength of this argument remains beyond the scope of this work.

Secondly, due to the character of Mikulčice as one of the most important centers of Great Moravia and at least the temporary residence of the ruling dynasty (Poláček 2008b), we can suppose some level of immigration. It was observed in industrializing and modern populations that infant feeding practices are one of the most conservative habits, which are retained in migrating families even when they face substantial changes in their living conditions and subsistence (Fildes 1995). As was discussed in Chapter 7.2.6.1, the higher variability of diet in females from elite classes may suggest significant immigration from the most distant areas. These women may have adhered to the infant feeding practices traditional in their place of origin.

Third, isotopic analysis of the adult diet as well as the data from other studies (e.g. Bigoni et al. 2013; Havelková et al. 2010) suggest some degree of socio-economic stratification within the population buried in the area of Mikulčice castle. These socio-economically distinct groups within the Mikulčice population could apply different weaning strategies. However, as stated previously, our sample is too low to perform the statistical analysis of potential socio-economic differences and, moreover, there is the confounding factor of age influencing the perception of social roles.

And finally, there are multiple factors beyond the common environmental and socio-economic context which may influence the individual decisions of mothers to wean either earlier or later than was the general norm. Regrettably, most of these factors are beyond our control when studying past populations or would require a thorough study based on much larger skeletal samples. Early weaning, contrary to the generally accepted norm, may be motivated by health conditions such as the bad health of the mother, the onset of the next pregnancy, problems with breastfeeding and infant suckling or the personal assessments of mothers that their children’s nutritional needs were not being met only by breastfeeding exclusively. Another set of reasons for early weaning comes from the socio-economic sphere: economic or subsistence needs may require the mothers to return to work or their absence from home may by motivated by their social roles (Gray 1995; Moffat 2001; Panter-Brick 1992; Simondon et al. 2001). A special case, when breastfeeding ceased abruptly, is the death of the mother (Simondon et al. 2001).

On the other hand, there are also certain circumstances motivating mothers to prolong breastfeeding. Again, they may arise from both health and the socio-economic sphere. It was observed that mothers tend to prolong breastfeeding when there is a shortage of food in the household (Mulder-Sibanda and Sibanda-Mulder 1999; Sellen and Smay 2001; Simondon et al. 2001). Prolonged breastfeeding may also result from the effort to avoid another pregnancy. There are no written remarks from before 1500 AD indicating that women were aware of the contraceptive effect of breastfeeding. It is, however, highly improbable that they would not have recognized that the return of menstruation is delayed when breastfeeding. This is a type of knowledge which would be probably transmitted by the oral tradition from one generation of women to another and may therefore escape the attention of medieval authorities (Fildes 1995). As another important factor, women tend to prolong breastfeeding, when their infants are weak, malnourished or sick (Mulder-Sibanda and Sibanda-Mulder 1999; Sellen and Smay 2001; Simondon et al. 2001). The infant health status may be of special importance in the case of our study. Working on non-survivors, we cannot exclude the fact that the observed dietary pattern differed from the general populace. From historical sources, we even know examples of human societies where breast milk was regarded as a beneficial food for sick and weak children and even adults (Salmon 1994). However, we do not have any indication that this practice occurred in the Great Moravian population. Another question is whether the consumption of breast milk on a special occasion of illness was sufficient in both quantity and duration to affect the isotopic values.

Another confounding factor, which we are not able to evaluate, is the sex of the individual. Differential parental investment in infants of different sexes are known from modern populations with high gender inequality (Jayachandran and Kuziemko 2011) and the most recent isotopic studies found this pattern also in archaeological populations (Eerkens and Bartelink 2013). Moreover in the Great Moravian population the different impact of socio-economic status on diet was observed in adults between both sexes. If this pattern was established already during infancy, the unknown proportion of males and females in our sample of sub-adults could shift the observed pattern.

And finally, we cannot exclude the possibility of wet-nursing. This practice is documented since Antiquity. During the Roman era, this practice was introduced to the countries dominated by the Romans (namely Britain). For continental Europe, the first written remarks regarding wet-nurses come from the beginning of the 2nd millennium. But regardless of the time period, with the exception of foundlings, wet-nurses were used only by royalty and the higher classes. It was not until the late Medieval period that this practice expanded into the middle class of artisans and shopkeepers (Fildes 1995). From the perspective of isotopic analysis, this practice may easily influence the observed pattern. When the isotopic values of a wet-nurse are different from those of the mother, the isotopic effect of breast-feeding may be either augmented or reduced. In the experimental study by Fuller et al. (2006b), nitrogen isotopic enrichment of exclusively breastfed infants ranged between 1.7-2.8‰. This is much lower than the range of isotopic variability of the female sample in this study as well as of many other historical populations (e.g. Herrscher 2003; Kjellström et al. 2009; Müldner and Richards 2005; Reitsema et al. 2010; Reitsema and Vercellotti 2012 and many others). The practice of wet-nursing was proposed as an explanation of the highly variable isotopic values of infants from the early modern population of Grenoble (Herrscher 2005). The engagement of wet-nurses – if practiced – took place most probably among Great Moravian elites from Mikulčice, which could be reflected as a seemingly more variable age at weaning.

7.3.4 Stable carbon isotopes

Based on the globally valid principles of geochemical processes, the change of diet reflecting breastfeeding and weaning behavior should be reflected not only in nitrogen isotopic values but should be observable also in carbon isotopic data. Fuller et al. (2006b) documented experimentally the existence of a trophic level effect of +1‰ in $\delta^{13}C$ values of breastfed infants. Subsequently, during weaning, carbon isotopic values show a more rapid decrease to the adult mean than $\delta^{15}N$ values, which led Fuller et al. (2006b) to declare $\delta^{13}C$ to be a good indicator for detection of the first introduction of supplementary food into a diet. Since then, many attempts have been made in order to find the above described pattern in the isotopic data of past populations. However, the absence of any evidence of a trophic level shift in $\delta^{13}C$ attributable to lactation is quite common (e.g. Herrscher 2003; Waters-Rist et al. 2011; Howcroft et al. 2014). Other studies were inconclusive (Dupras and Tocheri 2007; Eerkens et al. 2011; Howcroft et al. 2012; Haydock et al. 2013), usually with some individuals supporting and others contradicting this scenario. Though this Beaumont et al. (2015) hypothesized that, to interpret observed changes in isotopic values during the first years of life as a dietary change, the same pattern has to be observed in both carbon and nitrogen. Based on this premise, the authors attribute the results of the above mentioned studies to the impact of such factors as stress and growth.

If this principle postulated by Fuller et al. (2006b) is universally valid, applying it to our sampling strategy, we should observe:

1) For breastfed infants (as identified due to their $\Delta^{15}N_{t-b}$): either positive $\Delta^{13}C_{t-b}$ reflecting a trophic level effect of breastfeeding or insignificant $\Delta^{13}C_{t-b}$ based on the premise that due to the lower trophic level effect of 1‰ it will take a shorter time to reflect it in full (Fuller et al. 2006b) in the bone tissue.
2) For weaned infants: either negative $\Delta^{13}C_{t-b}$ reflecting the process of weaning or insignificant $\Delta^{13}C_{t-b}$ based on the premise that due to the lower trophic level effect of 1‰ it will take a shorter time to return to maternal values (Fuller et al. 2006b).
3) For infants with insignificant $\Delta^{15}N_{t-b}$: $\Delta^{13}C_{t-b}$ should be insignificant as well. Theoretically, $\Delta^{13}C_{t-b}$ may also be negative, reflecting the early stage of the weaning process.

In our sample, however, we do not see any clear pattern of decreasing $\Delta^{13}C_{t-b}$, which could be attributed to weaning. Moreover, isotopic values of certain individuals do not follow the above mentioned scenario. All breastfed and weaned infants show the values in accordance with the proposed hypotheses. But in case of individuals with insignificant $\Delta^{15}N_{t-b}$, there is a highly interesting group of three individuals (MIKS12, MIKS17, MIKS20) with highly increased $\Delta^{13}C_{t-b}$, which would be consistent with exclusive breastfeeding. However, a non-significant $\Delta^{15}N_{t-b}$ value for these children precludes such an interpretation. In some cases, the $\Delta^{13}C_{t-b}$ values were more positive or negative (±1.2‰) than is generally attributed to the trophic level effect of exclusive breastfeeding (Fig. 35).

And finally, regardless of the feeding status, some of the children show carbon isotopic values which could not be the result of breastfeeding. When taking into account the isotopic variability in the female sample (Tables 9 and 17) and the full trophic level effect of breastfeeding (1‰) carbon isotopic values of exclusively breastfed infants should be at most as high as -15.9‰ for the center and -14.9‰ for the hinterland sample. Several children, again especially from a center context (MIKS2, MIKS3, MIKS11, MIKS20), show higher carbon isotopic values than is the recommended maximum. In the rural sample, only one individual (JOSS02) rises slightly above the recommended range, which is mostly due to the one female outlier (JOSH27) with high carbon isotopic values (15.9‰). Though we accept the fact that our female sample may not represent the full range of values of Great Moravian females, the high isotopic values of some sub-adults are still surprising.

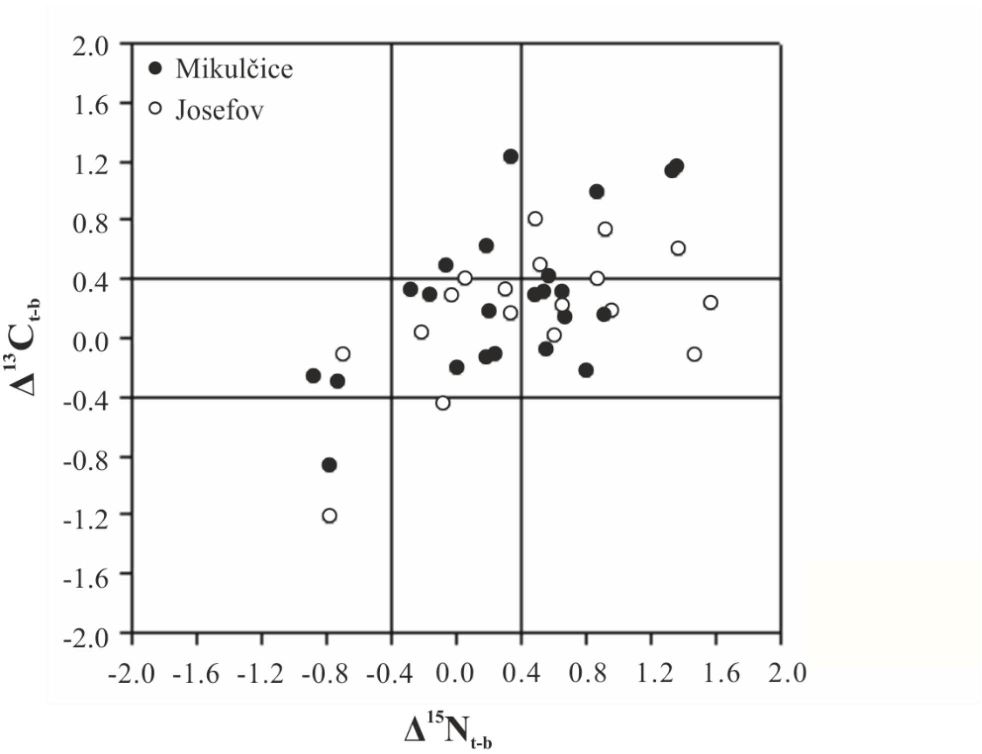


Fig. 35. $\Delta^{13}C_{t-b}$ in relation to $\Delta^{15}N_{t-b}$ in the Josefov and Mikulčice sample (modified according to Kaupová et al. 2014).

All these findings suggest the existence of others factors that could play a role in carbon isotopic variability in our sample of Great Moravian children. These values suggest the presence of a highly ^{13}C enriched food source in the diet of these children. As apparent from the isotopic values of the adult sample, millet was the common foodstuff during the Great Moravian period. The significant shifts in $\Delta^{13}C_{t\text{-}b}$ in individuals with insignificant $\Delta^{15}N_{t\text{-}b}$ may lead to the hypothesis that millet was introduced as a sort of weaning food. Extremely high carbon values observed in young infants with a present breastfeeding signal may, however, suggest that millet was introduced quite early into the diet of some infants, perhaps as one of the first dietary supplements, so its isotopic signal may be visible before any change in nitrogen isotopic values may be observed. Due to its being consumed in the form of porridge, millet represents an ideal type of soft mushy food which could be offered to infants and small children. The alternative to this is a consumption of the milk of animals fed with millet, which is however less probable taking into account the isotopic value of the animal data set. Another potential explanation may lie in the seasonal consumption of C_4 plants by either infants or their breastfeeding mothers. Seasonal variation in diet may be greatly reflected in the isotopic values of teeth samples, as well as in the rapidly remodeling bone of infants and young children. In bone samples of adult females, on the other hand, the averaged signal of more years may lead to less extreme values. Though it is impossible to describe the exact role of millet in the diet of Great Moravian subadults, it appears clearly that its use as a weaning food or seasonal variation in its consumption could blur a small trophic level effect of lactation in $\delta^{13}C$ and so it appears impossible to apply the premise pronounced by Beaumont et al. (2015) on the Great Moravian population.

7.3.5 Methodological concerns

The main constraint of this study lies in the relatively high number of individuals (15/41) whose feeding status we were not able to determine because it was impossible to be precise regarding the causes of their insignificant $\Delta^{15}N_{t\text{-}b}$. For these individuals several potential causes of the observed pattern may be suggested. Firstly, the individual may have never been breastfed at all or was breastfed by a wet-nurse with low nitrogen isotopic values. Secondly these children may have undergone the early phase of the weaning process at the moment of their death. Or theoretically, when children were breastfed for long enough, not only the tooth sample but also rapidly remodeling bone could reflect the breastfeeding signal in full. We are unable to be precise about the exact causes of this isotopic pattern because of the lack of information on the time necessary for the recording of the new nutritional regime in the isotopic composition of dental and bone tissues (Herrscher 2003) of a growing child. In addition, there is a lack of certainty regarding how long the metabolic nitrogen pool takes to equilibrate with the diet (Balasse et al. 2001). Another unknown factor is the bone turnover rate in the area of the mandibular base which greatly influence the length of breastfeeding required to balance the $\delta^{15}N$ value in bone to those in the tooth dentin.

Another potential limitation of our study may lie in the possible interference to our results of the different age composition of both samples, with the Josefov sample having a lower mean age (2.4 years) than the Mikulčice (2.7 years) sample. However this difference was not statistically significant (*Mann-Whitney test:* p=0.393) and, moreover, all performed statistical analyses were controlled for the age, which minimizes the potential effect of this factor. The complicating factor is the low number of individuals older than 3 years in the Josefov sample. Due to this, the potential effect of different age composition cannot be fully excluded.

As stressed by Beaumont et al. (2015) the effect of non-dietary factors, especially negative and positive nitrogen balance on ^{15}N values should also be considered. This may be of special importance in this study, which deals with the dietary signal immediately preceding the death of an individual. However the results of controlled animal feeding experiments (Ambrose 2002; Kempster et al. 2007; Williams et al. 2007) as well as rare results on human sub-adult bone and hair tissue (de Luca et al. 2012; Waters-Rist and Katzenberg 2010) show no relation between sub-adult isotopic values and the growth process, protein metabolism or nutritional stress (for more information on the impact of physiology/pathophysiology on sub-adult isotopic values, see Chapter 3). Up to now, breastfeeding (or dietary change in general) is the only factor which was documented to be reflected in the tissues of a growing child, as was proved by monitored studies of breastfed/bottle-fed babies and their mothers (Fogel et al. 1989; Fuller et al. 2006b).

If the assumption of Beaumont et al. (2015) is valid, the factor of biological/ nutritional stress may potentially explain the aforementioned unexpected isotopic values of the JOSS20 individual (4.8–5.6 years, $\Delta^{15}N_{t\text{-}b}$ = 0.6‰). During the osteological examination of JOSS20, the presence of *cribra orbitalia* was noted. However, this pathology was present in the majority of the Josefov sample of sub-adults, being found in 68% of the evaluated individuals. Additionally, JOS20 was scored as Grade a, which according to some authors (Bennike et al. 2005), is considered too mild to represent serious health problems. No other non-specific stress indicator was present in the case of JOS20 and this child does not appear to be stunted. To conclude this issue, we have no indication of any serious chronic health problems preceding the death of JOS20. However, without the knowledge of the exact time, which is needed both to incorporate the dietary signal into tissues and develop the pathological lesion, we cannot exclude with certainty the possibility of severe chronic stress impacting isotopic values. An alternative explanation of the observed feature lies in the increased consumption of higher trophic level food (such as fish or animal protein) shortly before death. The “post-weaning” increase in ^{15}N in dental tissue in some individuals is regularly observed in studies of this type (Beaumont et al. 2013; 2015; Eerkens et al. 2011; Henderson et al. 2014; Herrscher 2003; 2013). Moreover it was also noted at the population level in cross-sectional study (Schurr 1997).

In the case of two Mikulčice individuals (MIKS18, MIKS21), who were interpreted to be still breastfed at the age of four, the impact of non-dietary factors is less probable. Contrary to JOSS20, $\Delta^{15}N_{t\text{-}b}$ values of these individuals do follow the general pattern observed in the Mikulčice sample (Fig. 32). They are close to the level of significance, which is in accordance with a scenario of prolonged breastfeeding, since a substantial proportion of bone had been formed under this nutritional regime. Regrettably, low skeletal preservation prevented the osteological examination of these two individuals.

As another potentially confounding factor, we have no information on the types of weaning food consumed by Great Moravian children. There is a wide variation exhibited between cultures in the types of supplementary foods consumed during weaning (e.g. Sellen and Smay, 2001) often including highly enriched ^{15}N foodstuff such as fish. In the medieval population of Fishergate House in England (Burt 2013; 2015), weaned children (under 6 years) were suggested to consume a diet rich in fish and animal protein. But still the breastfeeding and weaning was clearly visible in the isotopic profiles of Fishergate children (Burt 2015). In this light, the diet of Great Moravian children would have to be really specific to compensate or even surpass the isotopic effect of the cessation of breastfeeding. We cannot however exclude the increase in the proportion of animal protein and/or fish at an older age (as discussed in the case of JOSS20).

7.3.6 The comparison of cross-sectional *vs.* intra-individual sampling strategy

The comparison of isotopic data between Great Moravian sub-adults and their potential mothers (Fig. 36) affirm well the choice of the intra-individual sampling strategy. The high variability of female isotopic data, observed in the Josefov (9.5 ± 0.7‰, N=20) and especially the Mikulčice sample (10.7 ± 1.0‰, N=36), precludes the use of the traditional cross-sectional approach. The range of female mean ±2SD (covering ≈95% of female variation), is useless here as a criteria for the determination of infant and young child feeding status. In the Mikulčice sample, this range is as broad as 4‰, which is at least equal to the full trophic level effect of exclusive breastfeeding. Accordingly, a cross-sectional approach of plotting $\delta^{15}N$ of dentin and/or bone samples against dental age and comparing with female values would lead to the misinterpretation of the feeding status of children nursed by mothers with low nitrogen isotopic values, who would be erroneously determined as weaned. This would be the case, for example, for the individuals MIKS10, MIKS11, MIKS15, MIKS18 and MIKS21 who – while interpreted as substantially breastfed based on $\Delta^{15}N_{t\text{-}b}$ – are within female group variability.

In the Josefov population, on the other hand, nearly all the samples show nitrogen isotopic values out of the female group variability without any trend of decreasing ^{15}N attributable to the weaning process: before 3 years of age the data is highly variable. The remaining 3 (!) cases aged more than three years are located within, or at least on the border, of the female group variability but they all - with the exception of JOSS20 bone sample - fall within the variability of the younger group. In the Mikulčice sample, the difference between younger (less than 2 years) and older (more than 2 years) individuals is more notable but even here we find individuals aged two years or less bordering the female group variability and being isotopically comparable with the older group.

Another point, in both the Josefov and Mikulčice samples, is that there are no the children (even among those interpreted as weaned or of undetermined feeding status) with nitrogen isotopic values located in the lower half of the female isotopic variation, i.e., lower than the female mean. This may suggest that either a certain minor proportion of their protein was still derived from breast milk or that their post-weaning diet was enriched in animal protein and/or fish when compared with adult females. A similar (even more significant) pattern was observed by Burt (2015) in the medieval population of Fishergate and was attributed to the high proportion of fish and animal protein in the diet of children. This would suggest some type of cultural buffering by providing children preferentially with high quality foodstuff.

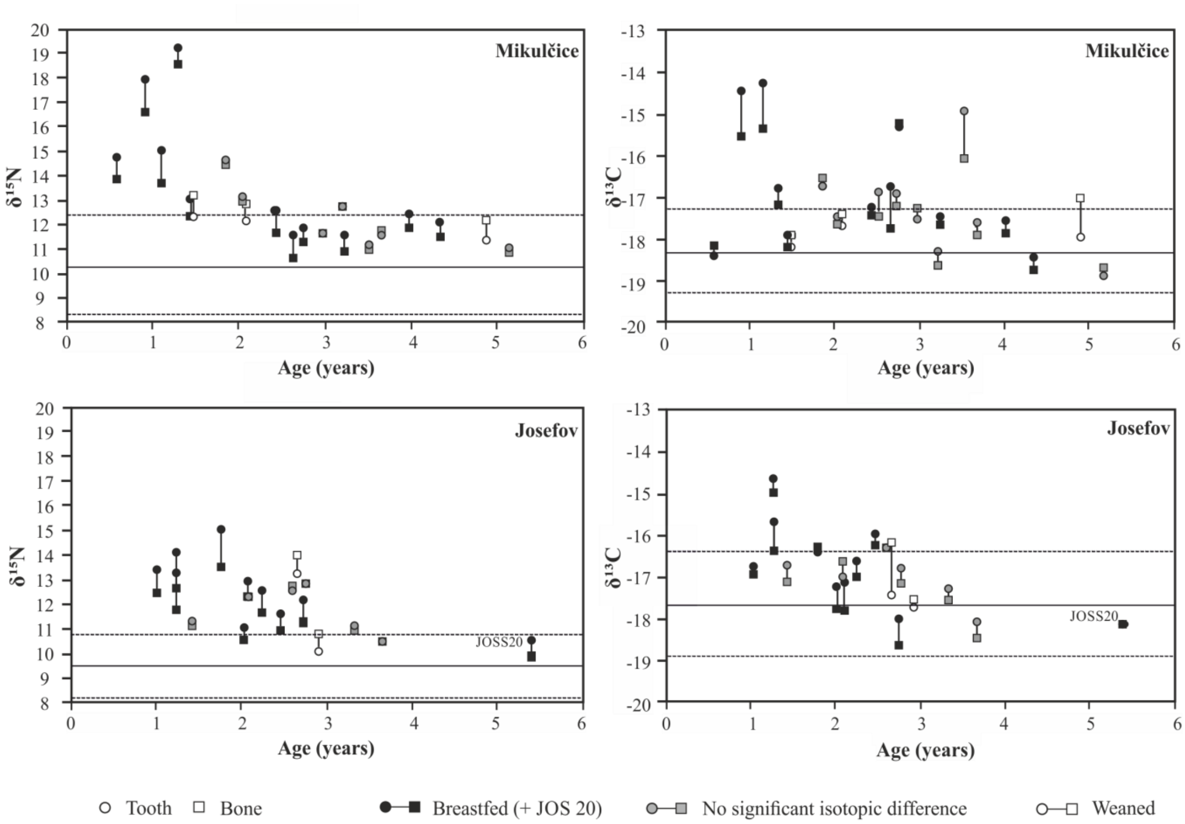


Fig. 36. The $\delta^{15}N$ and $\delta^{13}C$ values of sub-adult individuals plotted against the age at death and according to whether the sample was derived from bone or dentin (modified according to Kaupová et al. 2014). The three horizontal lines represent the adult female mean (solid line) and two standard deviations above and below this mean (dashed lines). Individual JOSS20 (discussed in the text) is labelled.

For carbon, especially in the Mikulčice population sample, the actual isotopic data does not reveal any trends attributable to breastfeeding and weaning behavior. In the Josefov sample, the pattern evokes at first glance the gradual decrease typical for the breastfeeding and weaning process, but firstly, the range between the highest and lowest values is several times higher (about 4‰) than the reported trophic level effect of exclusive breastfeeding. Secondly, the observed pattern is mainly caused by the high carbon isotopic values of one individual (JOSS2). This absence of any remarkable trend in carbon isotopic values is well in accordance with the conclusions derived from intra-individual results.

Additionally, there is another potential pitfall of the use of the female population mean which is crucial not only for this study but may be generally valid. Fuller and colleagues (Fuller et al. 2004; 2005) have clearly demonstrated the effect of pregnancy on isotopic data. Although there is a lack of substantial information on the nature and extent of isotopic shifts associated with lactation (Reitsema et al. 2013) there are some indications from non-human animal ecology that lactation may cause stable isotope shifts in females as well (Habran et al. 2010; Jenkins et al. 2001; Kurle 2002; Polischuk et al. 2001; Reitsema 2012a). Since the turnover rate of adult compact bone is low (Hedges et al. 2007), the bone samples reflect a mean isotopic signal for at least the last decade of an individual´s live (in the case of ribs). This may potentially blur any of the short term effects of either lactation or pregnancy, as demonstrated by Nitsch et al. (2010) with the skeletal material from Spitalfield.

Moreover, it was observed that specific dietary prescriptions may be imposed on young women in different cultures in relation to their pregnancy or lactation (Baumslag et al. 1989). Analogically, there could be a specific diet for weanlings and small children (Burt 2015; Sellen 2001) as well. All these factors make the use of adult females as a comparative group disputable and problematic because the isotopic values observed in female ribs are not necessarily the same as at the time that they nursed their babies.

For the above mentioned reasons, the intra-individual sampling strategy is the only possible choice to explore breastfeeding and weaning behavior in the Great Moravian population. It has to be stressed here that this part of the study was effectuated during the academic year 2011-2012. Since then some of the methodological problems discussed above may have been solved due to recent developments in the field of stable isotope analysis. The weight of collagen samples necessary to effectuate the isotopic measurement has decreased substantially during the last years, which enables us to apply the methodology of dentin serial sections (Beaumont et al. 2013; Henderson et al. 2014). This sampling allows us to solve some of the constraints mentioned above. It provides the dietary reconstruction with a higher temporal resolution. Also, it allows us to also explore the breastfeeding and weaning strategies in adult individuals, i.e., survivors, understanding the potential impact of the “osteological paradox”. Moreover it allows us to evaluate the effect of factors such as sex and socio-economic status. In the future, this more accurate method may help to formulate the dietary information from infancy and childhood in greater detail.

7.4 Relationship anmong health and dietary indicators

7.4.1 Diet and health in adult sample

As described in Chapter 4, multiple skeletal pathologies were suggested to be related to the quality of diet. Generally, increased prevalence of dental pathologies as well as nonspecific stress indicators were observed in populations with a protein-poor, monotonous diet based mainly on cereals (Armelagos and Cohen 1984; Bennike 1985; Brinch and Moller-Christensen 1949; El-Najjar 1976; 1982; El-Najjar et al. 1975; 1976; Hillson 1996; Larsen 1997; Larsen et al. 1995; Lukacs 1992; Milner 1984; Moore and Corbett 1971; 1973; 1975; Powell 1985; Sledzik and Moore-Jansen 1991). This chapter provides one of the first attempts to explore the relationship between isotopic indicators of diet and skeletal health markers at an individual level. This topic is dealt with in regard to the osteological paradox as posed by Wood et al. (1992). If the paradoxical interpretation is correct, individuals with skeletal lesion will show a better quality of diet which helped them to survive long enough to develop the lesion.

To address these issues, the same individuals who were sampled for stable isotope analysis underwent the osteological examination. But for several reasons, osteological analysis could be carried out on only two of the skeletal samples under study, namely on individuals from the Mikulčice and Josefov I samples, resulting in the sample of 102 individuals coming from both a center and hinterland context of the Great Moravian period. As stated in Chapter 6, all the individuals were aged either younger or older than 35 years. But because for most of the skeletal health indicators a strong correlation with the age may be supposed, we have attempted to achieve a more subtle differentiation by separating individuals older than 50 years. Regrettably, in some cases, age-at-death could not be estimated with such precision which resulted in the reduction of the sample size to 74 individuals.

First of all, we checked for the potential relationship between demographic data (sex and age-at-death) and the presence of different skeletal health indicators. There was no relation between the presence of *cribra orbitalia* and the sex of the individual. For the age-at-death, the results of statistical analysis were on the border of statistical significance ($p=0.044$) when divided into two age groups, with younger individuals being more likely to suffer from *cribra*. Neither sex nor the age-at-death influenced significantly the probability of having at least one caries lesion or ante-mortem tooth loss. But quite naturally, older individuals showed a significantly higher caries intensity (ICE) than the younger group. In accordance with other studies (Hanáková and Stloukal 1987; Larsen 1983; Larsen et al. 1991; Lukacs 1996; 2011; Stránská et al. 2008; Walker and Erlandson 1986), females showed a higher caries intensity than males. The presence of periodontal disease and periapical lesions were independent of the sex of the individual but, according to our expectations, they were significantly more probable in older individuals. The same pattern was observed for the severity of dental wear. Femur length differed significantly between males and females but not between younger and older individuals (Table 28). Since sex was a significant factor influencing both carbon and nitrogen isotopic data in a combined sample of Mikulčice and Josefov, all the analyses were performed for males and females separately. The most suitable statistical operation for the particular type of data was then chosen according to the significance of the age-at-death factor.

TABLE 28. The relationship between isotopic data, skeletal health markers and demographic indicators (p-values)[a]

	Sex	**Age (2 groups)[b]**	**Age (3 groups)[b]**
$\delta^{13}C$	**0.033[c]**	0.714[c]	0.294[e]
$\delta^{15}N$	**0.012[c]**	0.251[c]	0.779[e]
Cribra orbitalia	0.398[f]	**0.044[f]**	x
Caries presence	0.209[f]	0.127[f]	0.646[f]
ICE	**0.001[d]**	**<0.001[d]**	**0.014[e]**
Periodontal disease	0.126[f]	**<0.001[f]**	**0.010[f]**
Periapical lesions	0.117[f]	**0.001[f]**	**<0.001[f]**
Dental wear	0.887[d]	**<0.001[d]**	**<0.001[e]**
Femur length	**<0.001[d]**	0.304[d]	0.531[e]

[a] significant at <0.05 boldfaced.

[b]Age (2 groups) = younger/older than 35years; Age (3groups) = younger than 35/35-50/older than 50 years.

[c]*t-test*; [d]*Mann-Whitney test*; [e]*Kruskal-Wallis test*; [f]*Fisher exact test*.

As appears from Table 29 and Figure 37, there was no statistically significant relationship between the incidence of *cribra orbitalia* and isotopic values. As there were no individuals older than 50 years showing this skeletal non-specific stress indicator in our sample we have worked only with the younger/older than age 35 categories.

TABLE 29. Factors associated with the presence of cribra orbitalia: the results of the logistic regression (p-values)[a]

		Males			Females		
		N	$\delta^{13}C$	$\delta^{15}N$	N	$\delta^{13}C$	$\delta^{15}N$
Age	younger than 35	14	**0.038**	**0.038**	14	0.479	0.355
	older than 35	32			35		
Isotopic values (continuous)		46	0.724	0.947	49	0.398	0.883

[a] significant at <0.05 boldfaced.

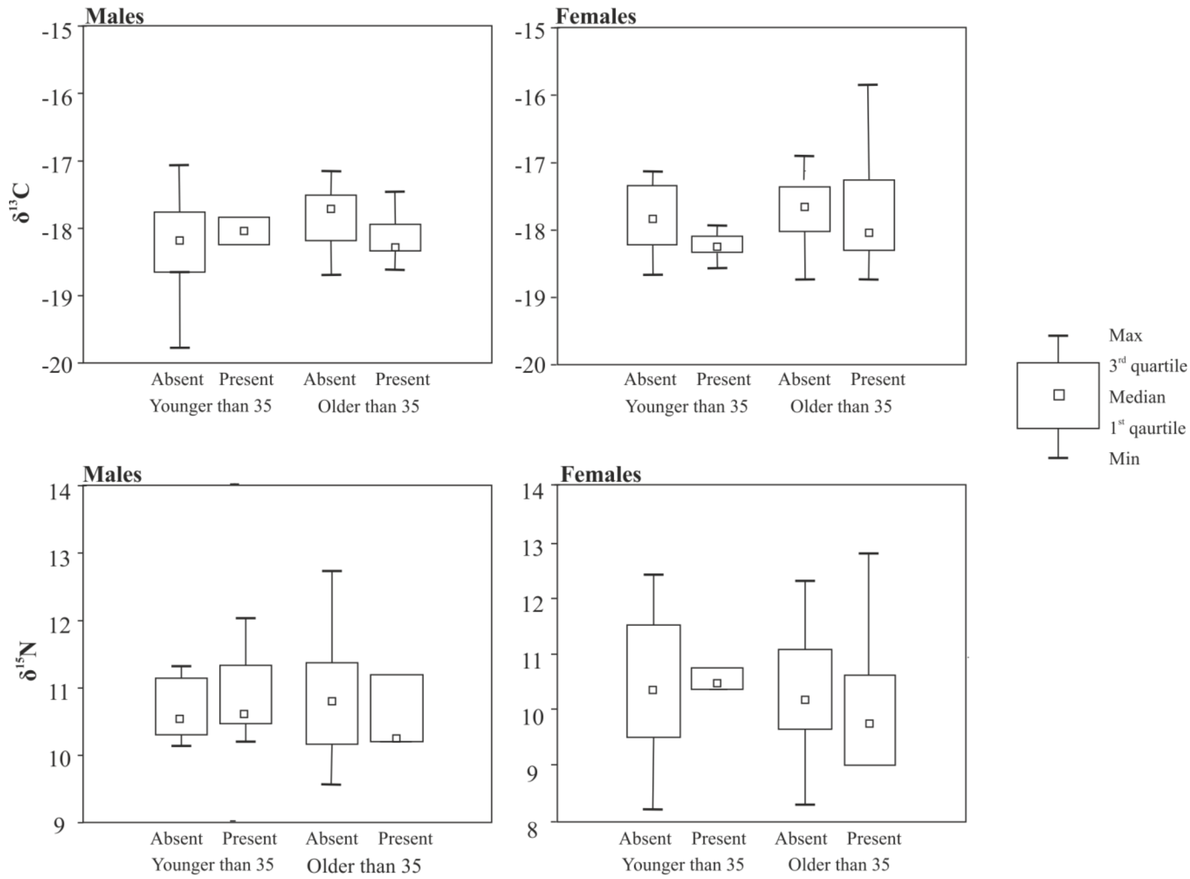


Fig. 37. The relationship between the presence *vs.* absence of *cribra orbitalia* and human isotopic values.

Since at least one caries lesion or *ante-mortem* tooth loss was a common finding in our sample regardless of the sex or age at death of the individual, we have used the *Mann-Whitney test* to check for the potential relationship to the isotopic indicators of diet. As in the case of *cribra orbitalia,* the presence of caries was not linked to either carbon or nitrogen isotopic values, though in the case of male carbon values, the p-value was close to the border of statistical significance (Table 30, Fig. 38).

TABLE 30. The relationship between the isotopic indicators of diet and the presence of caries: the results of the Mann-Whitney test

Males				**Females**			
N absent	**N present**		**p**	**N absent**	**N present**		**p**
15	29	**δ^{15}N**	0.750	10	44	**δ^{15}N**	0.327
		δ^{13}C	0.053			**δ^{13}C**	0.717

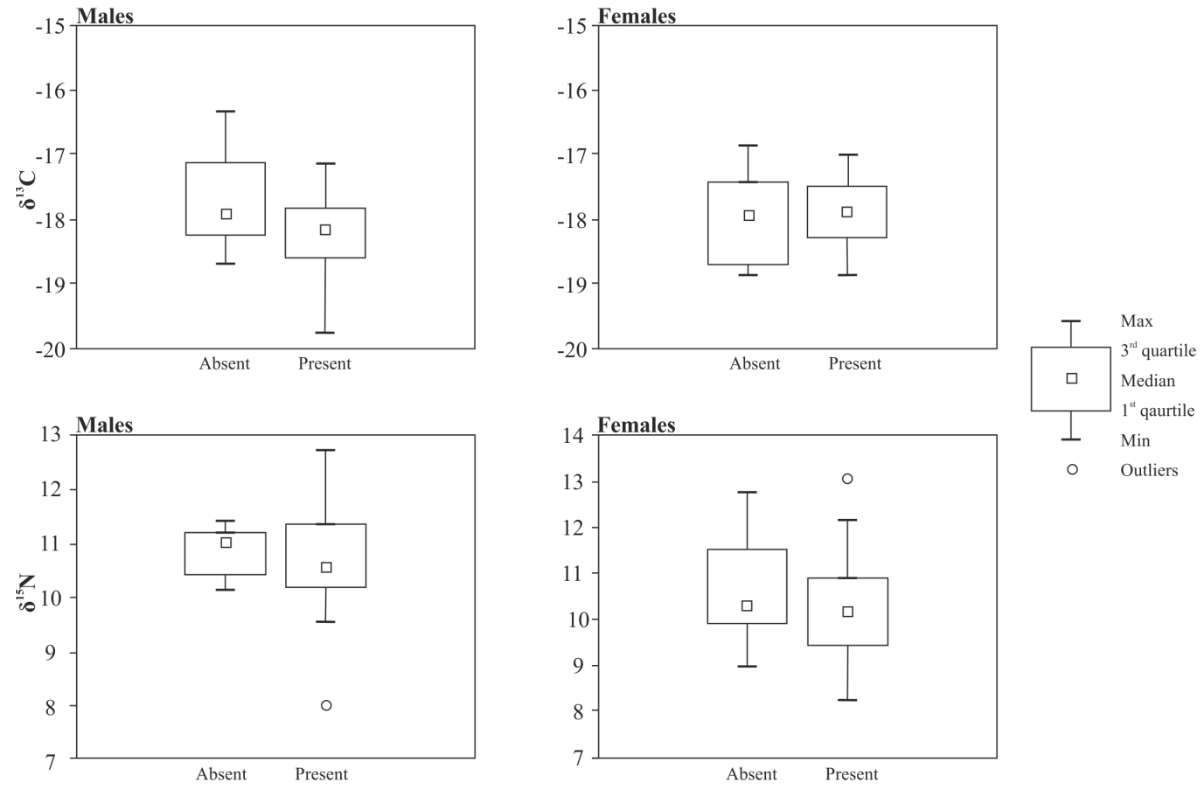


Fig. 38. The relationship between the presence *vs.* absence of at least one caries lesion or *ante-mortem* tooth loss and human isotopic values.

Caries intensity (ICE) proved to be much more closely linked to diet than the mere presence of caries. In accordance with the generally shared premise (Hillson 1996; Larsen 1997), the proportion of animal protein proved to be inversely associated with caries intensity, especially in the female sample (Table 31, Fig. 39). In males, the same trend was observed but was less obvious. When the sample was divided into three age categories, the statistical significance of the nitrogen isotopic data was lost in the male sample. In fact, for males, the statistical significance was most probably caused by several individuals with a high caries intensity and low δ^{15}N values. Much more convincing (and at the same time much more surprising) was the statistically significant relationship between ICE and carbon isotopic values in the male sample, with males with higher ICE showing lower carbon isotopic values. But again, the several outliers with a high ICE score may have significantly influenced the observed pattern.

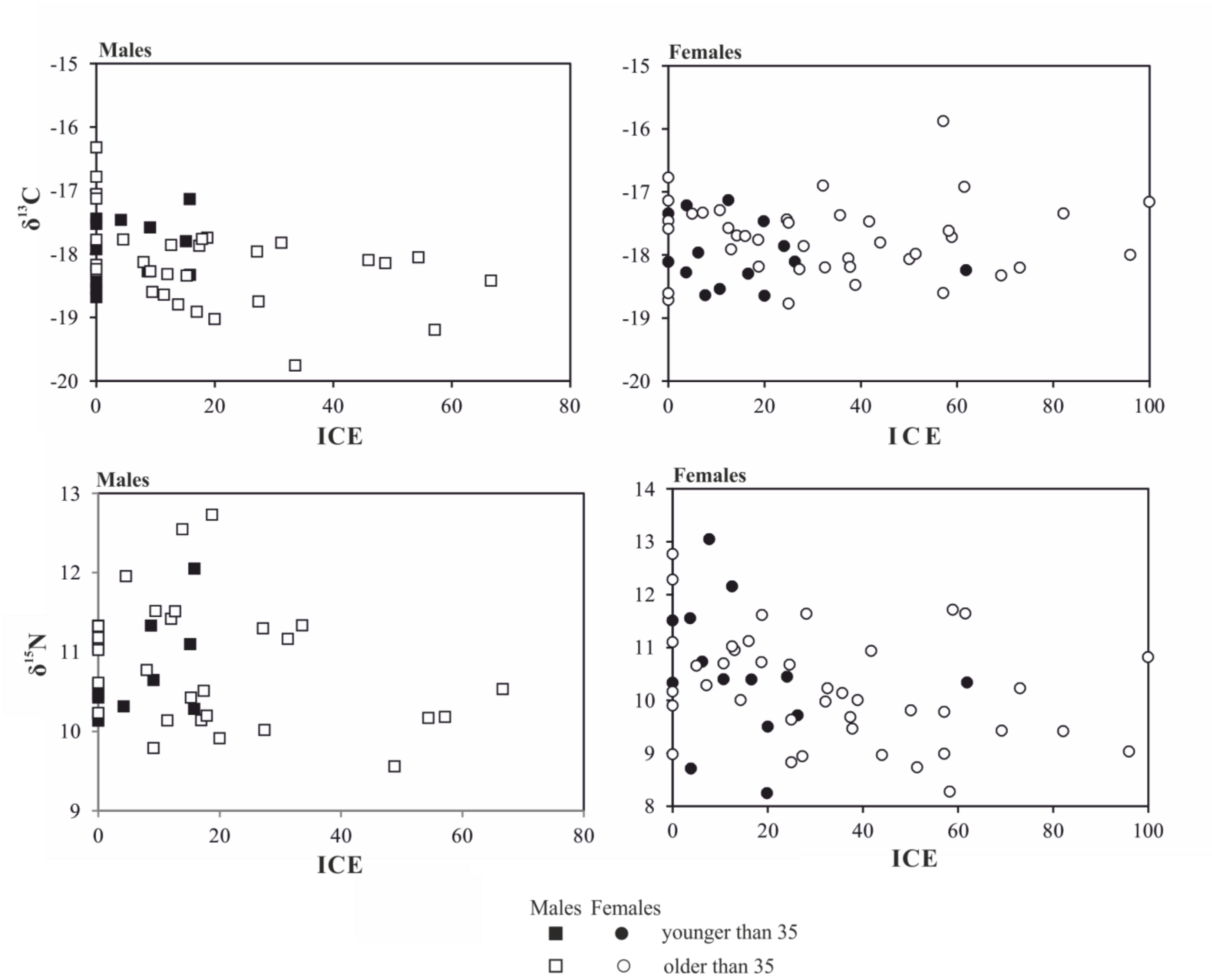


Fig. 39. The relationship between the caries intensity (ICE) and human isotopic values.

TABLE 31. The relationship between isotopic indicators of diet and ICE: the results of GLM analysis (p-values)[a]

		Males			Females		
		N	**$\delta^{13}C$**	**$\delta^{15}N$**	**N**	**$\delta^{13}C$**	**$\delta^{15}N$**
Age (2 groups)	younger than 35	13	**0.030**	**0.013**	14	**0.017**	**0.024**
	older than 35	31			41		
Isotopic values (continuous)		44	**0.020**	**0.026**	55	0.924	**0.021**
Age (3 groups)	younger than 35	13			14		
	35-50	13	0.171	0.111	15	**0.007**	**0.005**
	older than 50	7			10		
Isotopic values (continuous)		33	**0.041**	0.427	39	0.752	**0.022**

[a] significant at <0.05 boldfaced.

Other dental pathologies: periodontal disease and periapical lesions were actually rarely found in young individuals, which prevented (with the exception of periodontitis in the female sample) applying logistic regression. In the only case of periodontitis in females, the significant effect of nitrogen isotopic values was found, with those females consuming less animal protein being at a higher risk of developing periodontitis (Fig.40). This result remained valid even when applying the alternative 3 group age scoring system. In all the other cases, the *Mann-Whitney test* was performed on the individuals older than 35 years. In these cases no statistically significant relationship was found between dental pathologies and isotopic data (Tables 32 and 33, Figs. 40 and 41). For periodontitis in males, another set of logistic regression could be performed on the sub-sample of individuals aged as 35-50 and older than 50 years. Neither this analysis brought any statistically significant results. This type of analysis could not be performed in the case of periapical lesions because the assumptions of the logit model were not met.

TABLE 32. The relationship between the isotopic indicators of diet and the periodontal disease/periapical lesions in the individuals older than 35 years: the results of the Mann-Whitney test

	Males				Females			
	N absent	**N present**		**p**	**N absent**	**N present**		**p**
Periodontal disease	15	12	**$\delta^{15}N$**	0.283	x	x	**$\delta^{15}N$**	x
			$\delta^{13}C$	0.075			**$\delta^{13}C$**	x
Periapical lesions	21	8	**$\delta^{15}N$**	0.608	17	13	**$\delta^{15}N$**	0.080
			$\delta^{13}C$	0.510			**$\delta^{13}C$**	0.821

TABLE 33. Factors associated with the presence of periodontal disease: the results of logistic regression (p-values)[a]

		Males			Females		
		N	**δ^{13}C**	**δ^{15}N**	**N**	**δ^{13}C**	**δ^{15}N**
Age	younger than 35	x	**x**	**x**	14	**0.031**	0.071
	older than 35	x			31		
Isotopic values (continuous)		x	**x**	**x**	45	0.144	**0.004**
Age	younger than 35	x			14		
	35-50	11	0.162	0.287	12	0.332	0.233
	older than 50	6			6		
Isotopic values (continuous)		17	0.158	0.715	32	0.227	**0.012**

[a] significant at <0.05 boldfaced.

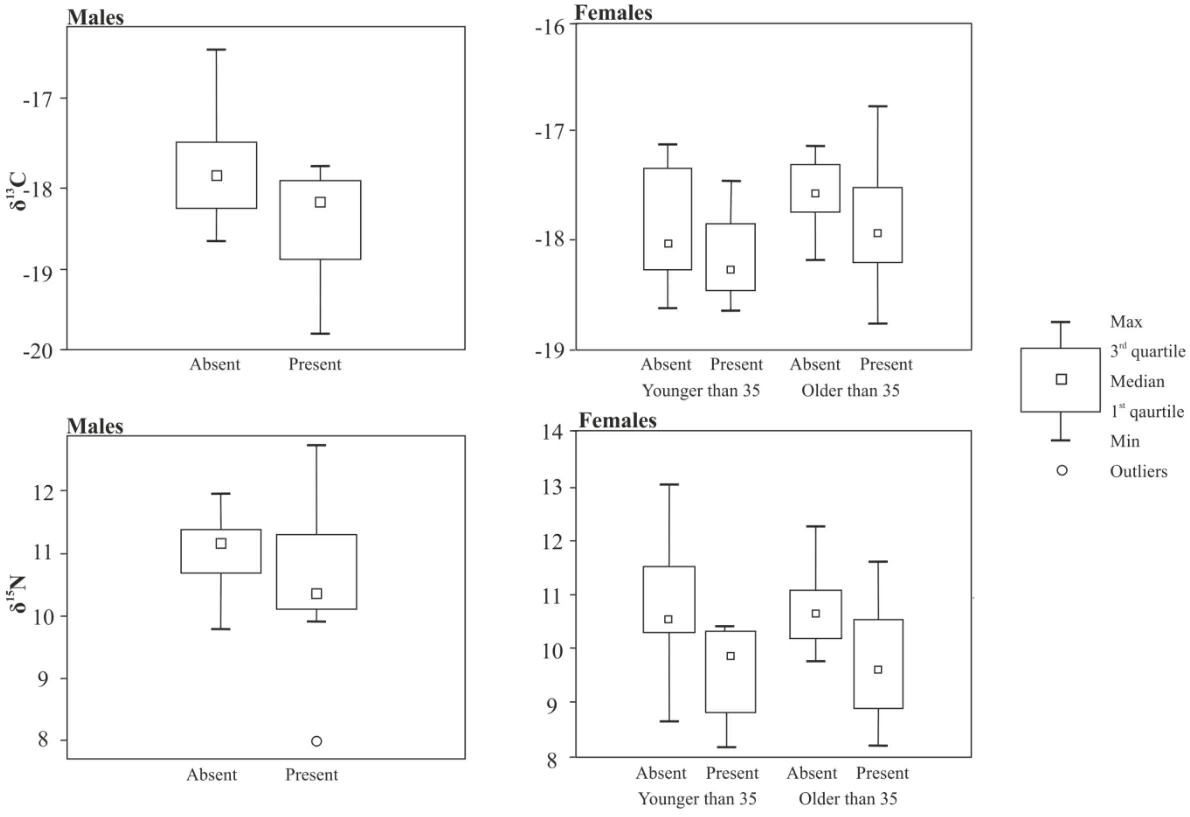


Fig. 40. The relationship between the presence *vs.* absence of the periodontal disease and human isotopic values. In case of males, the low number of individuals under 35 years with present periodontal disease prevented the classification according to age-at-death.

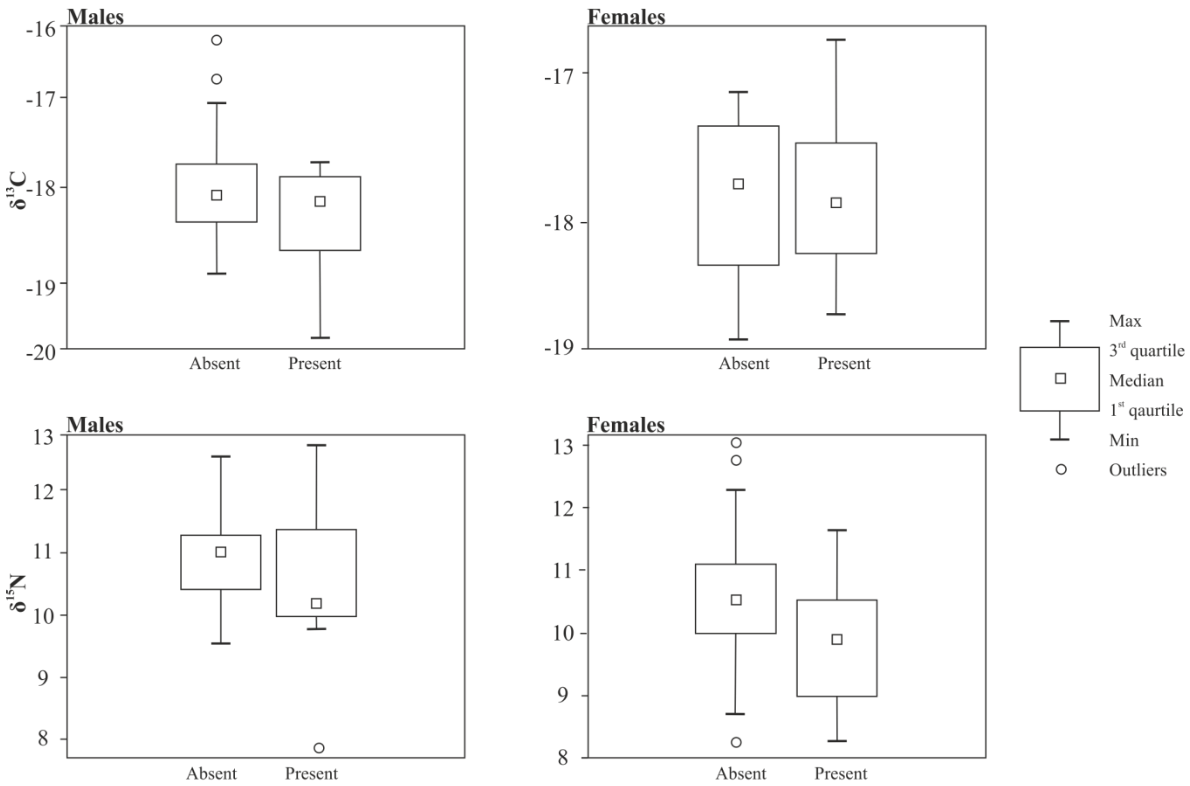


Fig. 41. The relationship between the presence *vs.* absence of the periapical lesions and human isotopic values.

As may be expected, dental wear showed a strong relationship to age-at-death. Besides this, carbon isotopic values appear to be inversely linked to the dental wear score in the male sample (Table 34). This suggests that males consuming less millet tend towards the higher wear score. Again, alternative age-at-death distribution did not change the statistical significance of the result. Females stand apart from this trend (Fig. 42).

TABLE 34. The relationship between isotopic indicators of diet and dental wear: the results of GLM analysis (p-values)[a]

		Males			Females		
		N	**δ^{13}C**	**δ^{15}N**	**N**	**δ^{13}C**	**δ^{15}N**
Age	younger than 35	13	**0.003**	**0.003**	14	**<0.001**	**<0.001**
	older than 35	29			34		
Isotopic values (continuous)		42	**0.005**	0.414	48	0.972	0.795
Age	younger than 35	13			14		
	35-50	13	**0.002**	**0.004**	12	**<0.001**	**<0.001**
	older than 50	6			7		
Isotopic values (continuous)		32	**0.007**	0.322	33	0.393	0.909

[a] significant at <0.05 boldfaced.

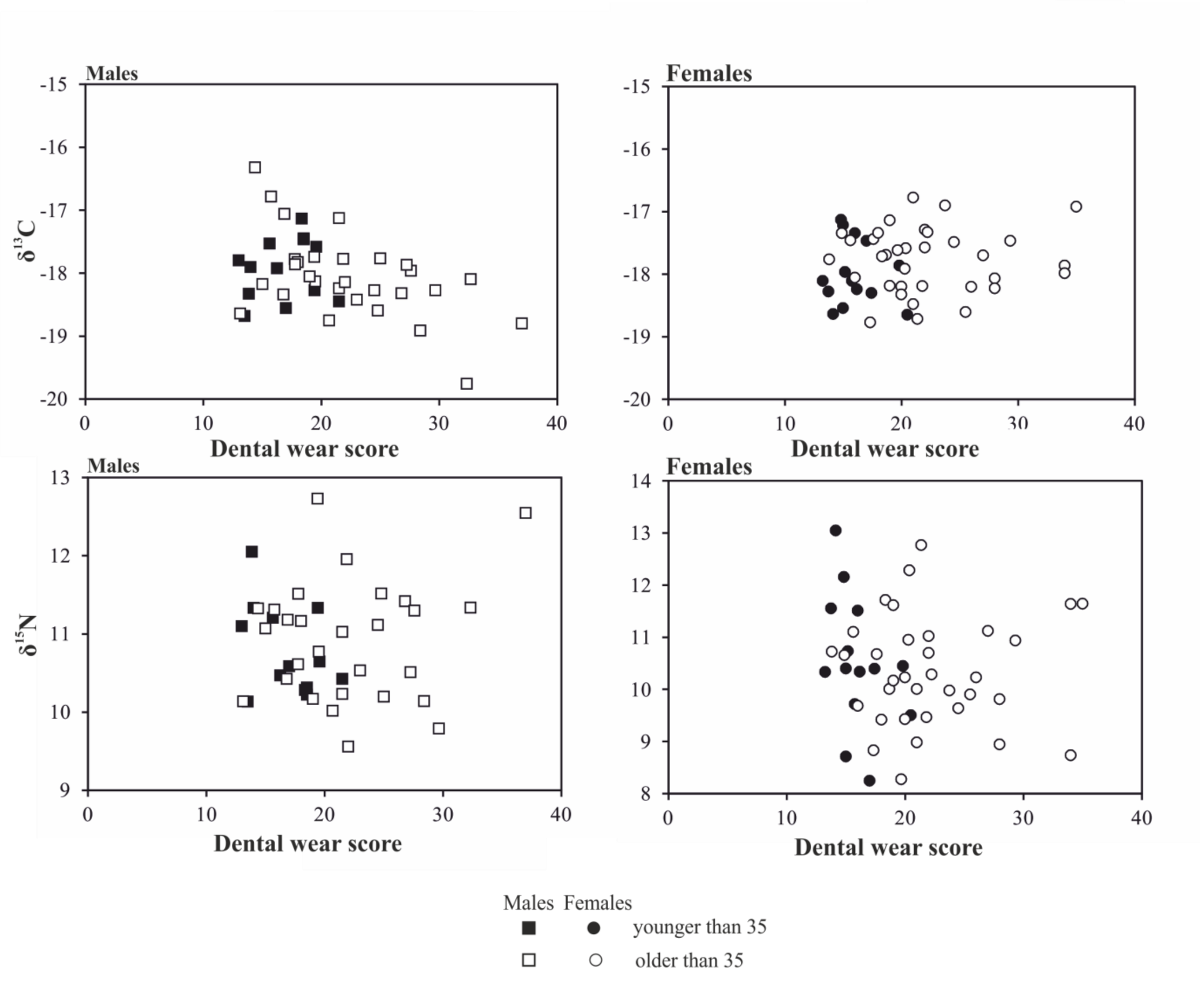


Fig. 42. The relationship between the dental wear score and human isotopic values.

As femur length showed no correlation to the age-at-death, Kendall's tau correlation was applied in order to describe the relationship between this approximation of adult stature and the isotopic indicators of diet. This analysis revealed no significant correlations either for the male or female sample (Table 35, Fig. 43).

TABLE 35. The relationship between the isotopic indicators of diet and the femur length: Kendall´s tau correlation (p-values)

Males			**Females**		
N		**p**	**N**		**p**
40	**δ^{15}N**	0.165	53	**δ^{15}N**	0.147
	δ^{13}C	0.113		**δ^{13}C**	0.403

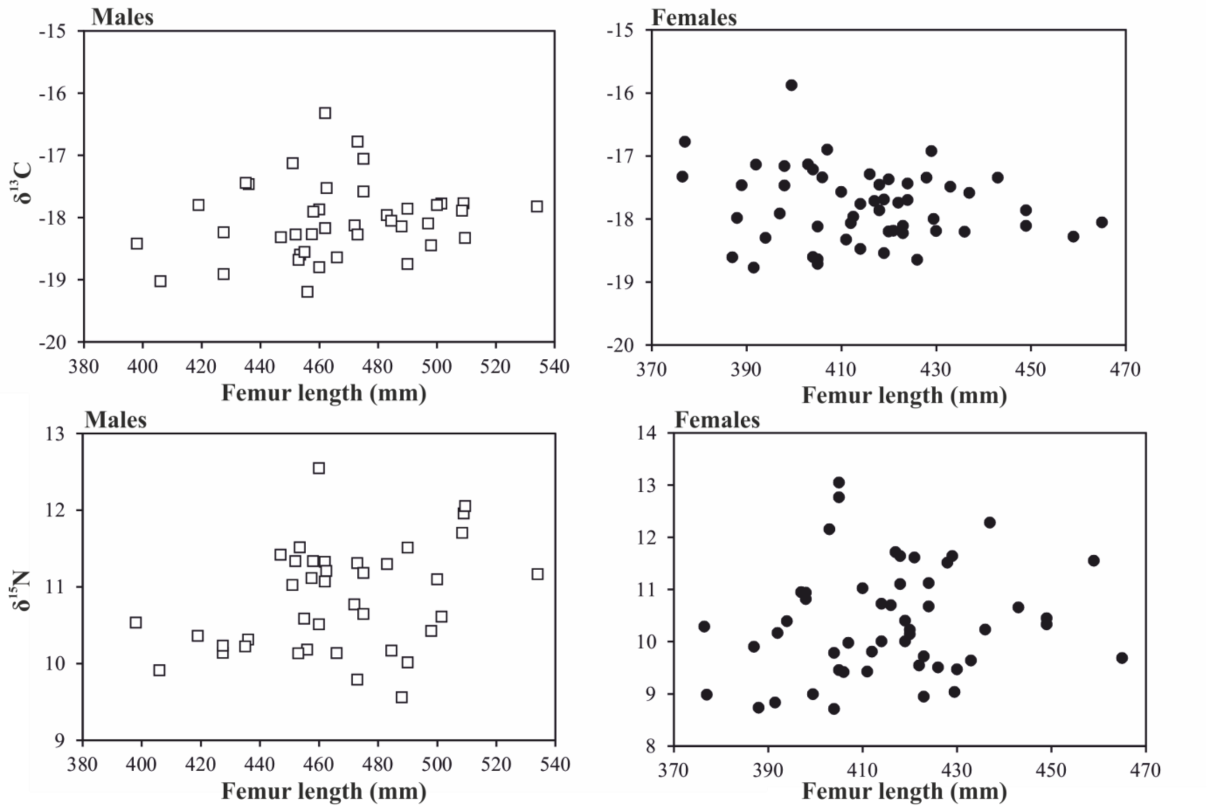


Fig. 43. The relationship between the femur lenght as an approximation of stature and human isotopic values.

From the data presented above it appears clearly that the quality of diet (as observed by stable isotope analysis) influenced the dental health of the Great Moravian population. Particularly in the female sample, lower consumption of animal protein was linked with increased cariogenesis and the higher prevalence of periodontal disease. This is in accordance with the generally shared premise (Hillson 1996; Larsen 1997), that a diet low in animal protein and rich in carbohydrates promotes both cariogenesis and periodontitis (Costa 1980; Frayer 1984; Larsen et al. 1995; Lukacs 1992; Owsley et al. 1987; Rose et al. 1993; Sledzik and Moore-Jansen 1991). Though there is some indication for the same pattern in the male sample, the relationship between dental caries and the proportion of animal protein was much less convincing. The potential explanation of this discrepancy of results between both sexes may lie in the higher variability of diet observed in Great Moravian females. A highly variable proportion of animal protein in the diet of females may have been reflected in the pattern of cariogenesis while the relatively stable proportion of animal protein consumed by males may have caused the absence of any observable impact. Much more surprising was the observed relationship between carbon isotopic values and caries intensity and dental wear in the male sample. Our data suggests that males consuming less millet suffered from more caries lesions and had more severely abraded teeth. The explanation of this pattern remains unclear. Theoretically, it may be linked to the texture of food. Millet was generally consumed in the form of porridge, so its higher consumption may suggest the individual favouring soft mushy foods which may result in lower dental wear and consequently lower cariogenesis (Hillson 2005; Larsen 1997). But the power of this explanation is weakened by the fact that the same pattern was not repeated in the female sample. However, females from the combined Great Moravian sample (and particularly those from the hinterland sample of Josefov) had consumed more millet than males. So the consumption of generally softer food (such as millet based porridge) may cause that the food texture was not a significant determinant of dental wear in the female sample.

Other skeletal health markers – *cribra orbitalia* and stature (as reflected by the femur length) showed no significant relationship to diet. In case of *cribra orbitalia*, this may be caused by their multi-factored origin, with the quality of diet being only one of the potential causes (Walker et al. 2009; Wapler et al. 2004). Regarding stature, it has to be taken into account that these two parameters (femur length *vs.* isotopic data) offer a snapshot into different periods of an individual´s life. While the attained stature reflects living conditions (including diet) during the period of growth and development (with the greatest impact during the first years of life) (Allen 1994; Bogin 1999; Carson 2008; Lejarraga 2002; Norgan et al. 2002; Rivera et al. 2003), the isotopic signature keeps the information about diet during the last years of individual´s live (Hedges et al. 2007). The temporal overlap of these two periods differs within the sample in relation to the age-at-death of the sampled individual. It was demonstrated in the population of medieval Italy that diet may change during the course of life in response to the acceptance of new gender and social roles (Reitsema and Vercellotti 2012). Subsequently adult diet does not implicitly correspond with the diet during childhood.

Although the quality of diet has been suggested many times as an explanation for observed changes in the health status of historical populations (Armelagos and Cohen 1984; Costa 1980; El-Najjar 1976; 1982; El-Najjar et al. 1975; 1976; Frayer 1984; Hillson 1996; Larsen 1997; Larsen et al. 1995; Lukacs 1992; Owsley et al. 1987; Rose et al. 1993; Sledzik and Moore-Jansen 1991), there is a striking lack of information on a direct relation between health indicators and isotopic values. Infrequently, a paper may be found describing actual isotopic values in pathological bone (Katzenberg and Lovell 1999; Olsen et al. 2014; Scorrano et al. 2014; White and Armelagos 1997). These are focused on the impact of actual pathological process or general changes in body metabolism accompanying severe disease rather than on the actual impact of the quality of diet on health status. To our knowledge, the only exception is the thesis by Yoder (2006), which, however, did not find any remarkable link between isotopic and palaeopathological data. The potentially confounding factor of this work may be the omission of the age-at-death factor which may have blurred any potential impact of diet on health status.

In this light, this work provides extremely important evidence of the observable impact of diet on dental health at an individual level seen in an archaeological population. However, our results are still based on a relatively small population sample and all the conclusions derived from them need to be confirmed by further studies.

7.4.2 Weaning strategies in relation to health

The extremely high importance of diet during the first years of life with the long term impact on growth and health is a well-documented phenomenon (Bogin 1999). Taking into account that weaning represents the greatest dietary change of childhood and at the same time a period of a high risk of biological stress (Demmelmair et al. 2006; Haines and Kintner 2008; McDade 2005; Palou and Pico 2009), special attention has been paid to the relation between health status and the feeding status of Great Moravian children. Regrettably, the number of individuals sampled for the stable isotope analysis precluded the statistical analysis of the relationship between diet and health at an individual level. All the analyses were limited to the comparison at the population level (center *vs*. hinterland).

According to the above mentioned premises, observed differences in weaning strategies should be reflected in observable differences in growth and health between center and hinterland population samples as follows: In the hinterland sample, one may expect the highest incidence of stress indicators after the age of 2 years. On the other hand, highly variable weaning strategies applied in the sample of Mikulčice should result in a more homogenous distribution of the palaeopathological data. Theoretically higher morbidity may be observed in the older age groups as a result of malnutrition resulting from the prolonged breastfeeding (Pearson et al. 2010).

The simple description of age distribution and the prevalence of non-specific stress indicators with regard to age are presented in Table 36 and Figure 44 for both Great Moravian centers and hinterlands. Logistic regression analysis was used to evaluate the relation between each of the three lesions and the type of residency (center *vs.* hinterland).

TABLE 36. Age distribution and prevalence of stress indicators by age category[a]

Age[b] **(years)**	**Age distribution**		**Cribra orbitalia**[c]		**Porotic hyperostosis**[c]		**Endocranial lessions**[d]	
	GMC	GMH	GMC	GMH	GMC	GMH	GMC	GMH
0.0-2.0	52	56	16(6)/38	9(1)/15	7(2)/23	1(0)/12	15/32 (12/22)	9/16 (6/11)
2.1-4.0	53	46	23(7)/31	14(4)/19	3(3)/24	1(0)/11	6/30	5/14
4.1-6.0	11	9	1 (0)/6	4(1)/6	0(0)/5	0(0)/4	1/7	0/4
0.0-6.0	28	47	5(2)/8	5(3)/7	0(0)/2	0(0)/2	2/6	2/7
Total	**144**	**158**	**45(15)/83**	**32(9)/47**	**10(5)/54**	**2(0)/29**	**24/75 (21/65)**	**16/41 (13/36)**

[a] GMC = Great Moravian center of Mikulčice; GMH = Great Moravian hinterland.

[b] For the purposes of sample description the individuals were divided into age groups. Individuals without recovered teeth, whose age could be estimated using growth and skeletal maturity (Scheuer and Black 2000; Stloukal and Hanakova 1978) were classified as 0.0–6.0 without further specification.

[c] No. of cases with present lesion (Grade b+c in parentheses) /No. of individuals with bone element present.

[d] No. of cases with present lesion /No. of individuals with bone element present (older than 1 year in parentheses).

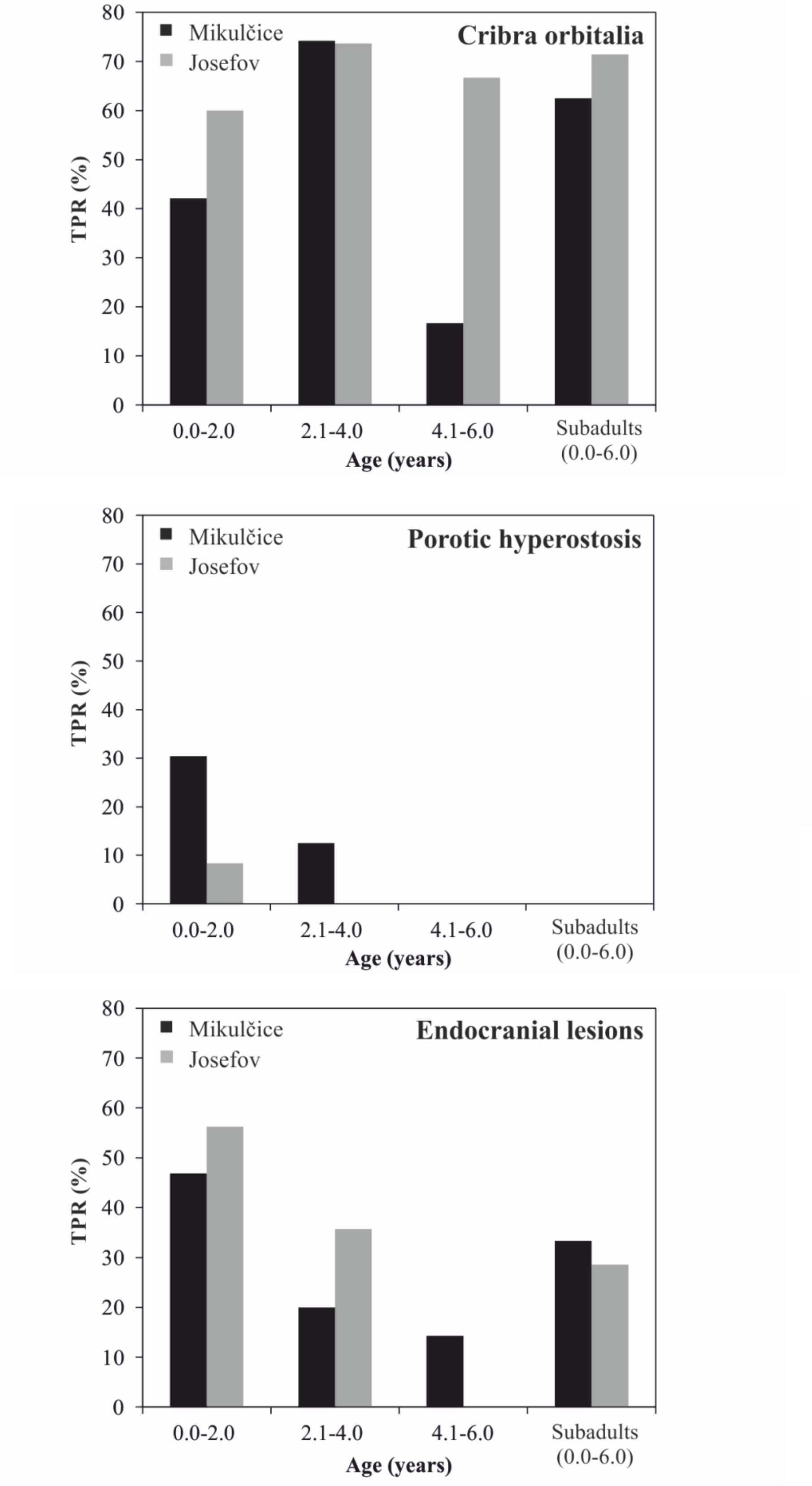


Fig. 44. True prevalence rate (TPR; % individuals with bone element present) of stress indicators in the Mikulčice and Josefov sample by age category.

The results of logistic regression adjusted on median age variable (Table 37) did not reveal any significant relation between the prevalence of stress indicators and the type of residency.

TABLE 37. Factors associated with the presence of non-specific stress indicators: the results of logistic regression (p-values)[a]

			Original dataset		Alternative dataset	
Pathology	**Explanatory variables**		**N**	**p**	**N**	**p**
Cribra orbitalia	**Context**	Center	75	0.165	75	0.782
		Hinterland	40		40	
	Age (continuous)		115	0.394	115	0.587
	Interaction[b]			0.282		0.432
Porotic hyperosotosis	**Context**	Center	52	0.168	x	x
		Hinteland	27		x	
	Age (continuous)		79	0.117	x	x
	Interaction[b]			0.520		
Endocranial lesions	**Context**	Center	69	0.344	59	0.344
		Hinteland	34		29	
	Age (continuous)		103	**0.010**	88	**0.006**
	Interaction[b]			0.653		0.701

[a] significant at <0.05 boldfaced.

[b]p Wald of the Interaction age* type of residency.

As expected from the results of previous studies (Lewis 2004, 2010), the presence of endocranial lesions is negatively associated with the age-at death. The observed trend of decreasing prevalence of endocranial lesions with increasing age was common to both center and hinterland sites (Interaction Age*Type of residency: p=0.653).

For the above discussed reasons (Bennike et al. 2005; Lewis 2004), we have repeated the statistical analyses, considering only individuals whose *cribra orbitalia* were scored as Grade b or c (in other words severe enough to reflect serious health problems) as positive. In the case of endocranial lesions, statistical operations were repeated after the exclusion of all individuals younger than one year, in which a non-pathological origin of this feature may be suspected. However, these changes of the data set did not influence the results of the statistical tests significantly. In the case of porotic hyperostosis, the number of individuals with severe lesions was too low to repeat the statistical test.

Although hinterland children seemed slightly shorter than those from the Mikulčice center in all bone dimensions (Fig. 45), the analysis of the standardized residuals of the polynomial regression (Table 38) revealed statistically significant differences only for the medio-lateral diameter of the humerus and femur. This finding is not sufficient to prove any systematic and significant difference in growth between these two groups of the Great Moravian population.

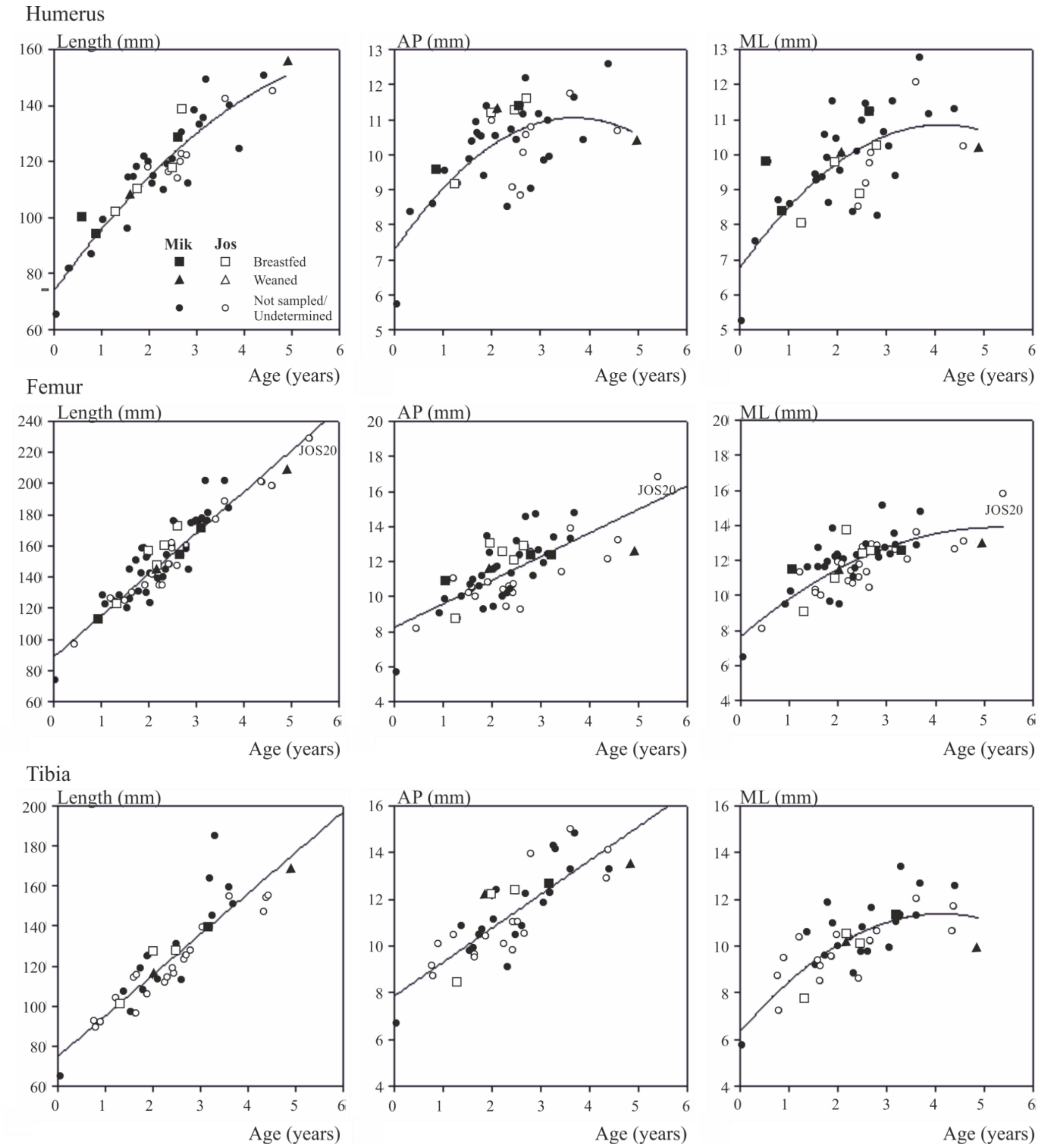


Fig. 45. Lineal regressions or second order polynomials for bone dimensions on dental age according to the GMC (Mik = Mikulčice) *vs.* GMH (Jos = Josefov) context and suggested feeding status (modified according to Kaupová et al. 2014). AP, ML = antero-posterior, medio-lateral diameter at the midshaft; Age = median dental age in years.

TABLE 38. The effect of type of residency on the standardized residuals of the polynomial regression on biometric measures upon dental age[a]

Bone	Dimension	Regression equation	Center			Hinterland			
			N	**Mean**	**s.d**	**N**	**Mean**	**s.d.**	**p**[b]
Humerus	**length**	HL = 73.78+23.64 (age)-1.62 (age)^2	31	0.06	1.01	10	-0.19	0.89	0.219
	AP	AP = 7.26+2.05 (age)-0.28 (age)^2	30	0.10	0.98	10	-0.31	0.94	0.268
	ML	ML = 6.75+1.98 (age)-0.23 (age)^2	31	0.17	0.98	10	-0.52	0.80	**0.020**
Femur	**length**	FL = 88.57+26.52 (age)	36	0.14	1.10	22	-0.24	0.73	0.197
	AP	AP = 8.23+1.35 (age)	36	0.11	0.98	22	-0.19	1.01	0.365
	ML	ML = 7.63+2.38 (age)-0.23 (age)^2	36	0.17	0.98	22	-0.28	0.95	**0.034**
Tibia	**length**	TL = 74.76+20.38 (age)	23	0.19	1.15	18	-0.24	0.68	0.293
	AP	AP = 7.86+1.45 (age)	23	0.03	0.97	18	-0.03	1.03	0.703
	ML	ML = 6.32+2.46(age)-0.30(age)^2	23	0.14	1.03	18	-0.19	0.86	0.287

[a] AP, ML = antero-posterior, medio-lateral diameter at the midschaft.

[b] *Mann-Whitney test* for independent data on the standardized residuals of the polynomial regression.

The results of other studies of this type suggest that the level of biological risk connected with the weaning varied among archaeological populations (Howcroft et al. 2012; Mays 2010; Pearson et al. 2010; Schurr 1997). The Great Moravian population belongs (together with those studied by Howcroft et al. 2012; Schurr 1997), to those with a lack of a causative relationship between the breastfeeding pattern and health status at the population level. This suggests that in Great Moravia, where the first children were weaned during the second year of life, probably a great majority of the population benefited from the advantages of prolonged breastfeeding. Regrettably, the applied sampling strategy does not allow us to determine the exact age of the first introduction of supplementary food. This supplementary food may have protected children from potential malnutrition, which could be linked with prolonged exclusive breastfeeding. Moreover, it is the first encounter with new pathogens from the first dietary supplements, which may represent the period of the highest risk of biological stress. As mentioned above, this question may be investigated more thoroughly in the future by applying the methodology of dentin serial sections, which enables us to describe the whole process of weaning instead of the mere detection of a significant reduction of breastmilk consumption which was noted in the case of this study.

It has also to be taken into account that the only observable difference in weaning strategies between both population groups was in the higher variability of infant feeding practices in Mikulčice sample. In reality, the proportion of children weaned both early and late may have been too low to affect the general health of the Mikulčice population in comparison with that of the hinterland.

Another factor complicating our interpretations is the absence of exact knowledge about bone turnover rate and the time necessary to incorporate the dietary signal and to develop bone lesions in sub-adult organisms. Subsequently the recording of bone lesions consecutively to physiological stress may present a different timetable than the recording of dietary modifications.

When looking at the results at an individual level (Fig. 46) *cribra orbitalia* were observed in all weaned children (N=4), but they were common among other groups (breastfed and undetermined) as well. When we focus solely on more severe lesions (Grade b), affected individuals are found in all dietary groups. Most of the cases of endocranial lesions were observed in the "breastfed" group. However, most of them are the youngest individuals in the whole sample so a non-pathological origin cannot be excluded (Lewis 2004). When we consider only individuals older than two years, the remaining four cases are again distributed among all three dietary groups. Based on this data, none of the dietary groups appear to be more buffered against biological stress. For the porotic hyperostosis (which was observed in just one case, scored as Grade a) and the analysis of growth (considering the low number of "weaned" individuals with measurable bone dimensions), it was impossible to describe the relationship between the type of diet and these nonspecific stress indicators.

For all these reasons, it is not possible to determine any relevant relation between infant and young child feeding practices and health status for the Great Moravian population.

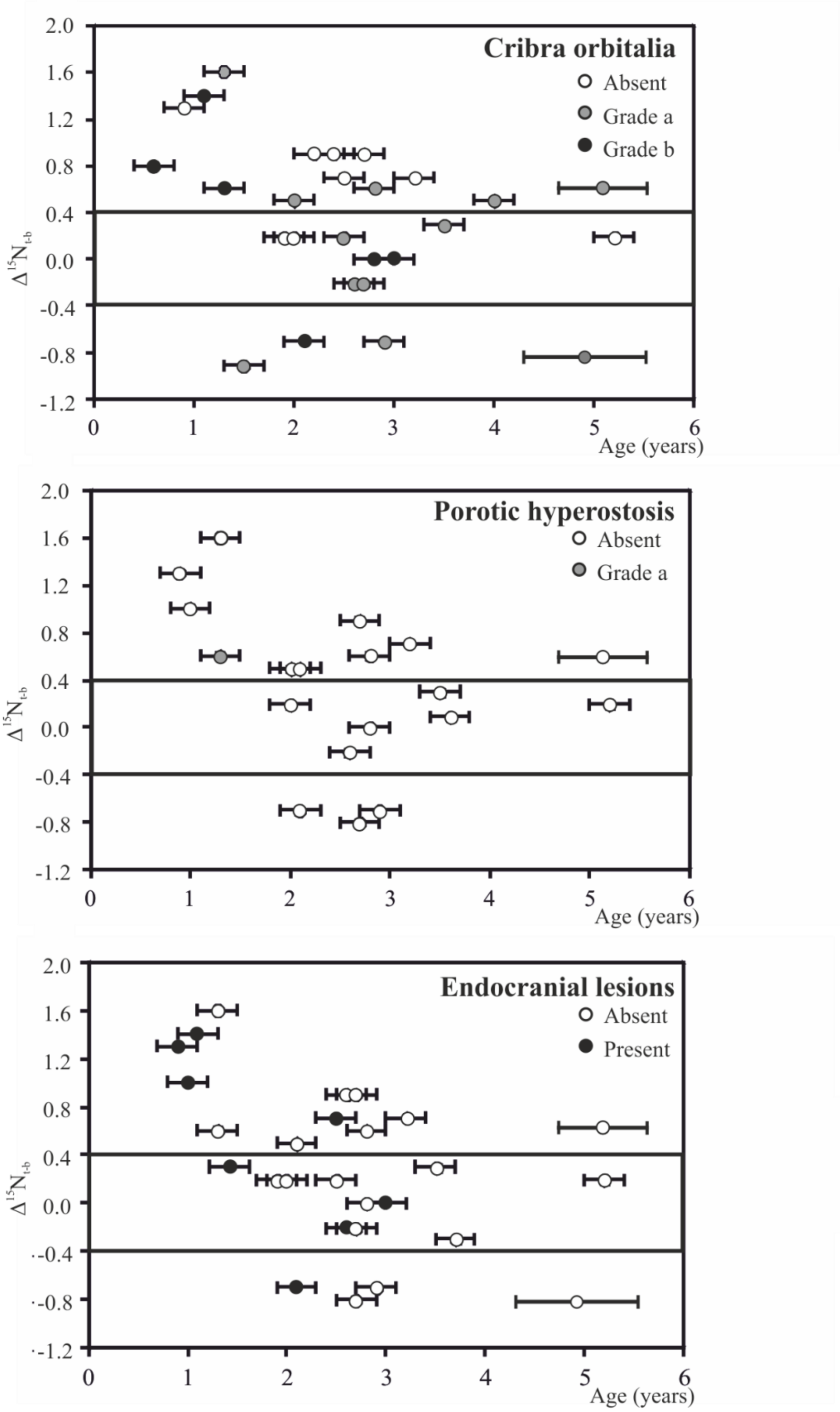


Fig. 46. $\Delta^{15}N_{t\text{-}b}$ according to the presence of non-specific stress indicators (for both Mikulčice and Josefov samples) (modified according to Kaupová et al. 2014).

8 CONCLUSION: DIET AND HEALTH PATTENS IN MEDIEVAL MORAVIA

The dietary analysis of the medieval Moravian population brings further testimony of the unprecedented importance of the social, economic, and religious changes the studied population had to face during the creation, establishment, and subsequent crisis and downfall of the Great Moravian Empire.

The observed differences in the quality of diet (namely in the dietary proportion of animal protein) among different population sub-groups reflected a relatively profound socio-economic stratification of Great Moravian society (i.e., the population of power centers *vs.* that of their hinterlands, and the socio-economically influenced differences in the diet of males from Great Moravian power centers).

In contrast, it seems that although there was an unprecedented development of Great Moravian power centers, the degree of urbanization still remained relatively low with no observable impact on husbandry practices and human dietary behavior. For example, the isotopic values of pigs showed no evidence of the “backyard” type of breeding typical of more urbanized areas (Hammond and O’Connor 2013). Also, the human isotopic data does not suggest the development of a group of urban poor with a homogenous and low-protein diet. In fact, the diet of people with a simple or non-existent grave inventory was more variable than those of elites, but still higher on average in animal protein when compared to the population of the Great Moravian hinterland. This should indicate the initial phase of the forming of a typical urban society with not all the people from the lower socio-economic classes having access to high quality foodstuff. However, this finding may also reflect a weakness in the estimation of socio-economic status of archaeological populations. If we consider grave goods or the type of grave as a main indicator of socio-economic status, the basic problem with this type of analysis remains the same. We can be relatively sure that individuals buried with rich goods or in elaborate graves were of high socio-economic rank, but we cannot ever be sure about the opposite, especially in the context of Christianization and the development of the hereditary social hierarchy of a medieval state—both of which may have influenced the form of burial (e.g. Poláček 2008b).

Although Christianity undoubtedly brought new ideas, rules and taboos into medieval society, covering virtually all areas of human life including diet, it seems that this did not influence the actual dietary behavior of the Moravian population, at least at the population level. The characteristic increase in the consumption of fish (reflecting an adherence to fasting rules), which was commonly found in more recent time periods

(Barrett et al. 2004; Müldner and Richards 2007; Salamon et al. 2008), and was also observed in some of the other populations of the earliest Christian converts and their offspring (Barrett and Richards 2004; Rutgers et al. 2009), was not observed in any of the sub-groups of the Great Moravian population. However, we cannot exclude the important role of freshwater products in the diet of some individuals. Namely the isotopic values of the three males buried in church interiors suggested that this grave location may reflect not only an exclusive position in the societal hierarchy but also a closer adherence to the Christian way of life. However, more individuals from the church interiors need to be sampled in order to confirm this finding.

When looking at the results of this study in the diachronic frame, it seems clear that the crisis preceding the downfall of the Great Moravian Empire did not influence the quality of diet of the population of its main power centers, at least in terms of access to animal protein. If there was some disruption of the food distribution system supplying non-autarchic centers, inhabitants were most likely able to find alternative sources of foods (such as wild fauna if animal protein was an issue). Also, it is possible the disruptions affected types of foods that were undetectable in the isotopic dietary signal. Although there was an apparent recovery of Moravian society in the 11th century following the period of disintegration and chaos after the downfall of the Great Moravian Empire (Hladík 2014; Lozny 2004), the quality of diet in this period did not reach the standards of the Great Moravian period. In particular, the diet of males was lower in animal protein than those of males from the Great Moravian hinterland sample. In addition, the increase in the consumption of millet may be explained by the impoverishment of society, although the impact of climatic change, with the culminating climatic optimum offering excellent conditions for the cultivation of millet, cannot be excluded entirely.

Seen in global terms, it is interesting that the diet of males seems to be a more sensitive indicator of social status and it changes more over time compared to the diet of females, which appeared more stable among both socio-economic classes and time periods. This most likely suggests a more strict division of roles within the male population.

We have noted the significant impact of diet on the dental health of Great Moravian people. It is one of the first examples of the direct link between diet and health status at an individual level. The finding of such a relationship in the case of dental pathologies is not surprising because dental tissues come into direct contact with consumed foods, so the composition and texture of food items may be directly reflected in the state of dentition. However, the relationship between diet and non-specific stress indicators is less straightforward, so the absence of any observable relationship is also not surprising. The observed findings of the relationship between nitrogen isotopic values versus dental caries and periodontitis agrees well with the generally shared opinion that a diet low in animal protein and rich in carbohydrates promotes both cariogenesis and periodontitis (Larsen 1997). The explanation of the relationship between carbon isotopic values versus caries and dental wear is much more problematic. Theoretically, the texture of the consumed food may be responsible for the observed pattern, with the higher consumption of millet reflecting the higher importance of soft food (such as millet porridge) in the diet, which may have contributed to the better state of dentition. However this hypothesis needs to be tested on a much bigger population sample.

For the sub-adult sample, high variability was observed in breastfeeding and weaning behavior, virtually excluding the existence of some unique and generally followed norms for the duration of breastfeeding. This variability was extremely high in the population of the power center of Mikulčice, while the hinterland sample showed a more homogenous pattern, suggesting the potential existence of some kind of norm in which the majority of the hinterland population was weaned after the age of two years. The observed differences in the variability of breastfeeding and weaning behavior between Great Moravian centers and hinterlands were not followed by an analogic pattern in health status. This may indicate that a majority of the Great Moravian population benefited from all of the advantages of prolonged breastfeeding.

However, the information recovered by the applied sampling strategy is limited to the detection of a substantial decrease in breast milk consumption. In the future, it will be possible to obtain more detailed analysis of the weaning process using improvements in mass spectrometry and sampling strategy. This may enable deeper analysis of the risks that weaning brought in the context of archaeological populations.

To conclude: the isotopic reconstruction of diet in the Great Moravian context helped to document the impact of known historical events on the lives of common people and to explain the observed patterns in health status, especially when dental health was in issue. It is the first study of a large skeletal sample, contributing new information not only on diet, but also in the wider sense, on the socio-economic system of a society that represents the actual basis from which Central Europe developed into its present form.

9 SOUHRN (CZECH SUMMARY)

9.1 Úvod

Období 9. a 10. století je ve středoevropském kontextu klíčové pro vývoj společnosti, kdy významné změny v sociální, politické i náboženské oblasti vedly k vytvoření základních pilířů středoevropské společnosti v její dnešní podobě. Velkomoravská říše pak představovala bez pochyby hlavní hybnou sílu tohoto procesu (Berend et al. 2013). Rozvoj Velké Moravy byl umožněn příznivými podmínkami počínajícího klimatického optima, vedoucího ke zvýšení zemědělské produkce, která vedla k nárůstu populace (Brázdil et al. 2005; Poláček 2001).

Přestože diskuze k otázce „státnosti“ Velké Moravy stále probíhá (např. Macháček 2012; Štefan 2011), proces formování této státní či spíše „protostátní“ struktury bezesporu bezprecedentně ovlivnil životní podmínky raně středověké populace. Archeologické, stejně jako písemné prameny ukazují na vysokou majetkovou a sociální stratifikaci velkomoravské společnosti. Další významné změny životního stylu pravděpodobně doprovázely přijetí křesťanství, které se ve sledované oblasti šířilo již od počátku 9. století. Přestože zejména v počátcích patrně zůstávalo omezeno na úzkou skupinu elitních vrstev společnosti, v průběhu 9. století se předpokládá jeho šíření do níže socioekonomicky postavených skupin a mimo hlavní centra. Charakteristickým rysem spojeným s formováním Velké Moravy byl i vznik a rozvoj extenzivních center, typicky situovaných na vyvýšených polohách říční nivy hlavních vodních toků (např. Poláček 2008b). Předpokládá se, že tato centra nebyla plně potravinově soběstačná. Přestože nejnovější výzkumy dokládají existenci polností (Látková 2015) a tím pravděpodobně i zapojení části obyvatelstva center do zemědělské produkce, role širšího zázemí v zásobování potravinami a klíčovými surovinami se zdá nezastupitelná. Toto ostatně dokládá i vysoká akumulace sídlišť a pohřebišť v blízkosti hlavních center (Dresler a Macháček 2008; Poláček 2008b).

Rozvoj Velké Moravy byl ukončen na počátku 10. století, kdy politická krize a následný vojenský atak vedl k zániku centrálních aglomerací, celkovému snížení počtu obyvatel a hustoty osídlení ve sledovaném regionu. Negativní roli mohla sehrát i klimatická změna, jejíž doklady v tomto období pozorujeme. S ní spojené záplavy mohly zasáhnout na prvním místě hlavní velkomoravská centra, která se v průběhu předcházejícího období rozšířila z vyvýšených poloh do níže položených oblastí říční nivy (Macháček 2013b).

První známky oživení společnosti na území zaniklé Velkomoravské říše jsou pozorovány už v posledních desetiletích 10. století (Macháček a Videman 2013), obnova společnosti a sídelní struktury pak byla dovršena ve století jedenáctém. Mohlo k němu přispět i tehdy vrcholící klimatické optimum (Svoboda et al. 2003).

Tyto jedinečné historické okolnosti umožnují studium různých aspektů lidského chování a zdravotního stavu v pravdě ojedinělém kontextu rychlých sociálních, ekonomických i náboženských změn, což staví dlouhodobě velkomoravskou populaci do centra zájmu již několika generací českých antropologů (např. Bigoni et al. 2013; Garcin et al. 2010; Hanáková a Stloukal 1987; Havelková et al. 2010; Sládek et al. 2015; Stloukal 1970; Stloukal a Vyhnánek 1976; Stránská et al. 2015; Velemínský a Poláček 2008). Izotopová analýza výživy a její vztah ke zdravotnímu stavu sledované populace přitom zůstává jedním z témat, kterým zatím až na výjimky (Halffman a Velemínský 2015; Smrčka et al. 2008) nebyla věnována systematická pozornost.

Základním principem izotopové analýzy výživy je, že izotopový signál konzumované stravy zůstává – při uplatnění globálně platných geochemických procesů – zachován ve tkáních konzumenta. Standardně využívaná v analýze výživy je přitom kombinace izotopových hodnot pro uhlík ($\delta^{13}C$) a dusík ($\delta^{15}N$). Hodnoty stabilních izotopů uhlíku nám umožňují určit některé základní charakteristiky ekosystému, ze kterého jedinec získával své potravní zdroje: umožňují rozlišit mezi suchozemským a mořským prostředím, stejně jako rozpoznat podíl C_3 a C_4 rostlin ve stravě jedince. Stabilní izotopy dusíku pak pomáhají určit pozici organismu v potravním řetězci. V případě člověka (jako omnivorního druhu) nás pak informují o důležitosti živočišných proteinů ve stravě. Přestože izotopové hodnoty sladkovodních ekosystémů jsou značně proměnlivé, kombinace hodnot pro uhlík a dusík může pomoci řešit i otázku konzumace sladkovodních ryb. Případné další zpřesnění v této otázce může (ovšem pouze za určitých podmínek) přinést i izotopová analýza síry ($\delta^{34}S$) (Ambrose a Norr 1993; DeNiro a Epstein 1978; 1981; Lee-Thorp 2008; Minagawa a Wada 1984; Nehlich et al. 2010; Richards et al. 2001; Schoeninger a DeNiro 1984).

Rutinně je pro rekonstrukci výživy využívána izotopová analýza kolagenu (např. Katzenberg 2007; Schwarcz a Schoeninger 2012), která je i základem této studie. Další možností je pak analýza minerální složky kostní tkáně, která může pomoci při řešení specifických otázek, např. konzumace C_4 rostlin v nízkém množství (Harrison a Katzenberg 2003). Její využití je však komplikováno problematickým stanovením dostatečné zachovalosti vzorku (Zazzo et al. 2004).

Kromě obecné rekonstrukce výživy je možné využít izotopovou analýzu k řešení specifických otázek. Nejčastěji – i v případě této studie – se jedná o stanovení délky kojení v minulých populacích. To je možné díky zvýšení trofické úrovně, ke kterému dochází v průběhu konzumace mateřského mléka a které je reflektováno nárůstem izotopových hodnot uhlíku a především dusíku (Fogel et al. 1989; Fuller et al. 2006b). Aktuálním trendem v této oblasti izotopové analýzy, který byl využit i v této studii, je takzvaná strategie intra-individuálního vzorkování (Beaumont et al. 2013; Eerkens et al. 2011; Henderson et al. 2014; Herrscher 2003) s využitím zubních tkání, jejichž izotopový signál se díky absenci remodelace (Balasse et al. 1999; Richards et al. 2002) časově liší od informace zaznamenané v kostní tkáni. Právě srovnání izotopových hodnot mezi kostí (obsahující informace z delšího období před smrtí) a vyvíjejícího se zubního kořene (nesoucího informaci z období bezprostředně předcházejícího úmrtí) bylo uplatněno na souboru nedospělých jedinců do 6 let věku, což umožnilo stanovit, zda u konkrétního dítěte došlo v průběhu jeho života k významnému poklesu konzumace mateřského mléka (Herrscher 2003).

Význam rekonstrukce stravy minulých populací je posílen tím, že výživa je jedním z klíčových determinantů zdravotního stavu, přičemž důležitý je nejenom dostatečný energetický příjem, ale i variabilita stravy (Hockett a Haws 2003; Kant a Graubard 2005; Kant et al. 1993; Lee et al. 2011). Výzkumy zdravotního stavu archeologických populací přitom naznačují, že jedním z hlavních faktorů ohrožujících zdravotní stav minulých populací je monotónní strava s vysokým obsahem obilovin, přičemž neznámější příklad zjevně představuje období intenzifikace pěstování kukuřice na americkém kontinentu (Kealhofer a Baker 1996; Knudson a Stojanowski 2008; Larsen 1994; 2001; Larsen a Milner 1994; Steckel a Rose 2002). Vzhledem k tomu, že kvalita výživy v prvních letech života má mimořádný potenciál ovlivnit zdravotní stav jedince nejen v tomto období ale i z dlouhodobého hlediska (Demmelmair et al. 2006; Haines a Kintner 2008; McDade 2005; Palou a Pico 2009), získává mimořádnou důležitost i studium vztahu mezi délkou kojení a zdravotním stavem sledované populace. Porovnání indikátorů zdravotního stavu a izotopových ukazatelů výživy na individuální úrovni však doposud, až na výjimky (Yoder 2006), nebyla věnována systematická pozornost.

9.2 Cíle práce

Hypotézy ověřované v rámci této práce lze rozčlenit do několika základních okruhů:

1) Prvním z nich je vliv socio-ekonomických a náboženských faktorů na výživu jednotlivých skupin velkomoravské populace. U obyvatel center a příslušníků vyšších socio-ekonomických vrstev lze předpokládat vyšší konzumaci živočišných proteinů. Na druhé straně pokud urbanizace velkomoravských center dosáhla určitého stupně, je možné předpokládat nárůst variability výživy v těchto souborech, podmíněný vytvořením vrstvy městské chudiny (Koepke a Baten 2005; 2008; Komlos 1998; Larsen 1997), pro niž je charakteristický nízký podíl živočišných proteinů ve stravě. Odrazem náboženských praktik je potom nárůst konzumace sladkovodních či mořských ryb jako doklad postních praktik (Barrett a Richards 2004; Müldner et al. 2009; Rutgers et al. 2009). Vzhledem ke gradientu šíření křesťanství od elitních skupin populace do nižších socio-ekonomických vrstev a z center do zázemí (Poláček 2008b), lze předpokládat vyšší konzumaci ryb u obyvatel center a výše socio-ekonomicky postavených jedinců.

2) Výše zmíněné faktory měly bezesporu potenciál ovlivnit nejen stravu dospělých jedinců, ale i výživu nedospělé části populace, nevyjímaje délku kojení. Vzhledem k finanční i materiálové náročnosti tohoto typu studie byly však ověřované otázky omezeny na porovnání trendů ve výživě kojenců a malých dětí mezi populací velkomoravských center a zázemí.

3) Dalším tématem práce bylo studium diachronních trendů ve výživě v souvislosti se zánikem velkomoravské říše a následnou obnovou společnosti v průběhu 11. století. V období finální fáze existence a zániku Velké Moravy (Macháček et al. 2014) bylo předpokládáno zhoršení kvality výživy u obyvatel velkomoravských center vzhledem ke zchudnutí populace a zhroucení redistribuce potravin. U populace 11. století se potom předpokládá opětovné zvýšení kvality stravy vzhledem k proběhlým adaptacím populace na nové klimatické a společenské podmínky (Hladík 2014; Lozny 2004). Pozitivní roli zde mohl hrát i zánik velkých center, protože bez nutnosti zásobovat rozhlehlá a lidnatá centra mohlo zůstávat více kvalitních potravin ve venkovských domácnostech (Koepke 2002; Komlos 1985; 1998).

4) Vzhledem k výše zmíněnému dopadu kvality výživy na zdraví jedince lze předpokládat odpovídající rozdíly ve zdravotním stavu. Ukazatelem kvality výživy sledovatelným pomocí stabilních izotopů je přitom zejména podíl živočišných proteinů ve stravě.

5) Nedílnou součástí izotopové analýzy výživy je i získání referenčních hodnot charakterizujících hodnoty lokálního ekosystému. Za tímto účelem je analyzován soubor zvířecích kostí. Tento soubor byl vybrán tak, aby umožnil maximálním možným způsobem ověřit působení potenciálních faktorů, které mohly ovlivnit izotopové hodnoty na bázi potravních řetězců. Konkrétně jsme ověřovali následující hypotézy: a) Aplikované chovatelské a zemědělské praktiky ovlivnily izotopové hodnoty domestikovaných zvířat oproti zvířatům volně žijícím. Dále, b) specifické prostředí říční nivy ovlivnilo izotopové hodnoty zvířat chovaných v blízkosti velkomoravských center oproti zvířatům chovaným v širším zázemí. c) Izotopové hodnoty prasat chovaných v blízkosti center jsou ovlivněny postupující urbanizací (Hammond a O'Connor 2013) a proto se liší od hodnot domestikovaných přežvýkavců. A konečně, d) změna klimatických podmínek a rozvoj zemědělských praktik ovlivnil izotopové hodnoty mladohradištního souboru zvířat z 11. století oproti zvířatům z období Velké Moravy.

6) Přestože tato studie je primárně založena na analýze vzorků kolagenu, byl v jejím rámci ověřen i potenciál analýzy minerální složky kostní tkáně na vybraném souboru lidských kostí. V rámci souboru zvířecích kostí byl pak ověřován potenciál izotopové analýzy síry.

9.3 Materiál a metody

K testování výše zmíněných hypotéz byla využita izotopová data celkem 5 kosterních souborů datovaných do velkomoravského (9. – počátek 10. století) a mladohradištního (11. století) období. Studované soubory je tedy možno rozdělit podle socio-ekonomických a diachronních kritérií na: 1) „Velkomoravská centra", reprezentované soubory Mikulčice - hrad (N=70) a Pohansko – Severovýchodní předhradí (N=56), dále 2) „Velkomoravské zázemí", které zastupují velkomoravské hroby pohřebiště Josefov (viz. „Josefov I"; N=32) a konečně 3) „Mladohradištní soubor" bez zahrnutí socio-ekonomického kritéria (N=31), který pochází z menších či neúplně odkrytých pohřebišť Louky od Břeclavska a Josefov – mladohradištní fáze (i.e., Josefov II). V případě nedospělých jedinců vzorkovaných pro analýzu kojení se, jak už bylo uvedeno výše, studie omezila na porovnání populace velkomoravského centra (Mikulčice – Hrad, N=23) a zázemí (Josefov, N=18). Izotopové hodnoty minerální složky kostní tkáně byly měřeny ve výběrovém vzorku 30 jedinců z lokalit Mikulčice (N=10), Josefov I (N=10) a Louky od Břeclavska (N=10).

Srovnávací soubor zvířat byl vybrán tak, aby reprezentoval 3 výše zmíněné hlavní celky. S výjimkou velkomoravských center (Mikulčice N=42, Pohansko N=10) však nebylo možné získat dostatečné množství zvířecích kostí přímo z daných lokalit, proto byl soubor zvířecích kostí z Josefova (N=3) doplněn o materiál z blízkého velkomoravského sídliště Mutěnice – Zbrod (N=15). Mladohradištní soubor zvířat pak zastupoval materiál z této fáze sídliště Kostice – Zadní Hrůd (N=10). Hodnoty stabilních izotopů síry byly měřeny v menším souboru 22 zvířat z Mikulčic (N=18) a Pohanska (N=4).

Osteologické zpracování za účelem analýzy vztahu výživy a zdravotního stavu bylo z řady důvodů omezeno na soubory z Mikulčic jako zástupce velkomoravských center a Josefova jako reprezentanta velkomoravského zázemí. V případě souboru dospělých byli osteologicky zhodnoceni stejní jedinci, u nichž byla provedena i izotopová analýza. V případě nedospělých, nízký počet jedinců, u kterých byly měřeny izotopové hodnoty, neumožňoval provedení jakékoliv statistické analýzy sledovaných osteologických ukazatelů. Soubory byly proto rozšířeny na 144 jedinců z Mikulčic a 158 jedinců ze zázemí, kde díky nízkému počtu jedinců v dané věkové kategorii odkrytých v Josefově došlo k rozšíření souboru o obdobně datovanou lokalitu Prušánky I.

Vzorky kolagenu byly připraveny metodou podle Longina (1971) v modifikaci podle Bocherense (1992). Vzorky kosti pocházely v případě dospělých jedinců ze žeber, případně kostí ruky či nohy (zejména článků prstů). V případě nedospělých jedinců byly vzorky kosti odebrány z *basis mandibulae*, vzorky dentinu potom pochází z kořene vyvíjejícího se zubu. Konkrétní zub byl vybrán podle věku jedince, přednostně byly vzorkovány první a druhé dočasné stoličky. Vzorky minerální složky kostní tkáně byly připraveny metodou podle Garvie-Lok et al. (2004) v modifikaci podle Salesse et al. (2013) s využitím kostního materiálu zbylého po extrakci kolagenu. Izotopová měření byla provedena pomocí *Europa Scientific EA elemental analyzer* a *Europa Scientific 20-20 IRMS* v odborné spolupráci se společností Iso-Analytical Limited, Crewe z Velké Británie.

Odhad věku a pohlaví u dospělých jedinců byl proveden autorkou práce u souborů z lokalit Mikulčice, Josefov I a II a Prušánky I s využitím následujících metod: Brůžek a Velemínský (2008), Murail et al. (2005), Ferembach et al. (1980) a Schmitt (2005 a 2008). V případě lokalit Pohansko – Severovýchodní předhradí a Louky od Břeclavska byla základní demografická data dodána kolektivem Vladimíra Sládka. Věk nedospělých jedinců byl odhadnut rovněž autorkou práce s pomocí metod Liversidge et al. (1998), případně Moorrees et al. (1963), Smith (1991), Scheuer a Black (2000) a Stloukal a Hanáková (1978). Z indikátorů zdravotního stavu byla v případě dospělých sledována přítomnost *cribra orbitalia* (Nathan a Haas 1966), přítomnost zubního kazu a intenzita kazivosti (ICE) (Stloukal a Vyhnánek 1976), dále i přítomnost periodontitidy a periapikálních lézí. Zubní abraze byla hodnocena metodikou podle Scott (1979). Jako ukazatel výšky postavy byla použita délka kosti stehenní (M1 dle Bräuer 1988). V případě nedospělých jedinců byla hodnocena přítomnost endokraniálních lézí s využitím kritérií dle Lewis (2004) a stejně jako u dospělých byla sledována přítomnost *cribra orbitalia*. Kromě toho byla s využitím stejné metodiky (Nathan a Haas 1966) sledována i přítomnost *hyperostosis porotica*. Měřena byla délka diafýzy, předozadní a medio-laterální průměr středu diafýzy kosti stehenní, holenní a pažní (Mays et al. 2009).

9.4 Izotopová data: výsledky a diskuze

9.4.1 Izotopové hodnoty souboru zvířat

Soubor volně žijících zvířat, stejně jako většina vzorků skotu, ovcí/koz a prasete domácího vykazuje izotopový signál typický pro C_3 ekosystém. Výjimkou je pouze jeden ze vzorků skotu (MUTF10) jehož hodnoty ukazují na relativně významnou roli C_4 rostlin (prosa) v jeho stravě. Několik dalších vzorků potom vykazuje hodnoty stabilních izotopů uhlíku kolem -19‰, což nevylučuje roli prosa jako doplňkového krmiva. Skupinou domestikovaných zvířat, jasně se vydělující jak izotopovými hodnotami dusíku, tak uhlíku, jsou psi a drůbež. Jejich izotopové hodnoty nesou jasný signál konzumace C_4 rostlin. Tyto hodnoty nereflektují pouze pozici těchto druhů v potravním řetězci, ale také jejich těsné sepjetí s člověkem. Psi i drůbež jsou chováni v bezprostřední blízkosti lidských sídel a krmeni především zbytky lidské potravy, případně konzumují odpadky včetně exkrementů. Jejich strava tedy více než u ostatních druhů reflektuje stravu lidskou (Guiry 2013; Reitsema et al. 2013). Zajímavé jsou v tomto kontextu izotopové hodnoty prasat, které jak v zázemí, tak v centrech, odpovídají hodnotám domestikovaných přežvýkavců. Nesdílejí tedy trend viditelný u psů a drůbeže, jak je tomu v silněji urbanizovaných oblastech, kdy se mění způsob jejich chovu (Hammond a O'Connor 2013). Tato skutečnost ukazuje, že přestože velkomoravská centra dosáhla stupně rozvoje bezprecedentního pro danou oblast, stupeň urbanizace zůstával stále relativně nízký, umožňující extenzivní formu chovu prasat. Statistická analýza neprokázala významný rozdíl mezi volně žijícími a domestikovanými druhy (při vyloučení psů a drůbeže) ani mezi zvířaty chovanými/konzumovanými v centru a v zázemí. To ukazuje, že hospodářské praktiky ani specifické přírodní podmínky v oblasti říční nivy se neodrazily významným způsobem na izotopových hodnotách zvířat. Jediným statisticky významným faktorem tak bylo časové hledisko, kdy mladohradištní zvířata vykazovala nižší hodnoty stabilních izotopů dusíku než zvířata z období velkomoravského. Zahrnutí či vyloučení skupiny psů a drůbeže nemělo na tyto výsledky vliv. Při bližším pohledu je však patrné, že pozorovaný rozdíl je způsoben především nízkými izotopovými hodnotami dvou vzorků prasat domácích. Vzhledem k nízkému počtu vzorkovaných prasat, jakož i celkové velikosti mladohradištního souboru zvířat, však není možné rozhodnout, zda se jedná pouze o relikt vyplývající z malé velikosti souboru či o reálný odraz změny ve způsobu chovu prasat. Tuto skutečnost je každopádně nutné vzít v potaz při hodnocení diachronních změn ve stravě lidí.

Hodnoty souboru ryb vykazovaly vysokou variabilitu, v rozmezí hodnot typickém pro evropské sladkovodní druhy (Fuller et al. 2012b; Reitsema et al. 2013; Vika a Theodoropoulou 2012). V tomto ohledu je důležité, že hodnoty souboru ryb jsou statisticky významně odlišné od souboru suchozemských zvířat, což ukazuje, že jejich významná konzumace by se měla odrazit v izotopových hodnotách jak dusíku, tak uhlíku (Reitsema et al. 2013). Izotopové hodnoty uhlíku dvou vzorků ryb (MIKF40 a MIKF42) jsou však hodnotám suchozemských zvířat blízké. Není tedy možné vyloučit – zejména při individuální preferenci konkrétních druhů – určité zkreslení izotopových hodnot lidí, kdy může být konzumace ryb méně patrná. Z tohoto důvodu jsme přistoupili k analýze stabilních izotopů síry. Tato analýza má však uplatnění při rekonstrukci konzumace sladkovodních ryb pouze v určitých případech (pokud se hodnoty v lokálním suchozemském a vodním prostředí liší), což může být i při znalosti lokální geologie obtížně předvídatelné (Privat et al. 2007). Proto byla provedena pilotní studie na souboru ryb (N=7) a suchozemských zvířat (N=15). Výsledky této studie bohužel ukázaly naprostou nevhodnost této analýzy v kontextu Velké Moravy. Izotopové odnoty ryb totiž vykazovaly vysokou variabilitu, utvářející dvě skupiny extrémních hodnot. Hodnoty všech suchozemských zvířat ležely mezi těmito extrémy. Jako možné příčiny tohoto jevu jsou diskutovány diagenetické změny, využívání odlišných vodních toků a nádrží či variabilita izotopových hodnot v rámci říční nivy (Privat et al. 2007; Trembaczowski 2011; Ward et al. 1999).

9.4.2 Lidské izotopové hodnoty souboru dospělých

Izotopová data velkomoravského souboru jsou charakteristická pro stravu založenou na suchozemských organismech, s významným podílem C_4 rostlin (prosa). Porovnání s izotopovými hodnotami zvířat přitom ukazuje, že se jednalo o tzv. přímou konzumaci prosa (např. ve formě prosné kaše) a že tedy zdrojem zvýšených hodnot nebylo mléko a maso zvířat prosem krmených. Kombinace hodnot pro uhlík a dusík a jejich porovnání se souborem zvířat také ukazuje, že ryby nebyly důležitou složkou jídelníčku na populační úrovni. Nemůžeme ale vyloučit jejich zvýšenou konzumaci v případě některých jedinců. V širším středoevropském kontextu zapadá náš soubor mezi ostatní soubory slovanských populací (Lightfoot et al. 2012; Reitsema 2012b; Reitsema et al. 2010), což dále potvrzuje hypotézu o spojení této plodiny právě se slovanským etnikem (Barford 2001).

Porovnání výživy mezi soubory pocházejícími z velkomoravských center (Mikulčice *versus* Pohansko) neprokázalo statisticky významný rozdíl. Zdá se tedy pravděpodobné, že i přes nepochybně nižší stupeň v hierarchii velkomoravské státní struktury, i přes zjevné zchudnutí populace a předpokládaný rozpad systému distribuce potravin na sklonku velkomoravského období (Macháček et al. 2014), si tato skupina obyvatel Pohanska dokázala udržet obdobnou kvalitu stravy, kterou pozorujeme v Mikulčickém souboru. Toto platí přinejmenším, co se týče parametrů sledovatelných pomocí izotopové analýzy, tedy zejména podílu živočišných proteinů ve stravě. Možné vysvětlení přináší probíhající archeozoologická analýza materiálu z Pohanska (Dresler a Macháček, ústní sdělení), která ukazuje na abnormálně vysoký podíl lovu volně žijících zvířat. Ta mohla nahradit proteiny pocházející z domestikovaných druhů.

Biologické faktory (pohlaví a dožitý věk) neovlivňovaly statisticky významně stravu ani v jednom souboru z velkomoravských center. Oba soubory však sdílejí stejný trend ve vztahu výživy a socio-ekonomického postavení jedince. Jde o statisticky významný dopad socio-ekonomického postavení (přestože vyjádřeného v každém souboru odlišným způsobem) na podíl živočišných proteinů ve stravě mužů. Muži pohřbení s bohatou hrobovou výbavou (v případě Mikulčic) či v hrobech s konstrukcí (v případě Pohanska) vykazovali vyšší podíl živočišných proteinů ve stravě. V souboru žen nebyl obdobný vztah nalezen ani v jednom případě. Jako možné příčiny tohoto jevu jsou diskutovány kulturně podmíněné preference jednoho z pohlaví (Reitsema a Vercellotti 2012), či rozdílná úroveň migrace mezi pohlavími (Kjellström et al. 2009).

Díky absenci rozdílů mezi oběma soubory byla pro další statistické analýzy data z Mikulčic a Pohanska sloučena do jednoho souboru označovaného jako „Velkomoravská centra“. Při porovnání se souborem ze zázemí (lokalita Josefov I) byl zřejmý statisticky významný rozdíl v případě stabilních izotopů dusíku, kdy populace zázemí konzumovala v průměru méně živočišných proteinů oproti obyvatelům center. To spolu se socio-ekonomicky determinovanými rozdíly ve výživě, pozorovanými v rámci populace center ukazuje na pokročilou socio-ekonomickou stratifikaci velkomoravské společnosti. Ne všichni obyvatelé tedy měli rovný přístup k potravním zdrojům. V samotném souboru zázemí nebyly socio-ekonomicky determinované rozdíly ve výživě pozorovány. Statisticky významný byl však mezipohlavní rozdíl ve výživě, kdy strava žen obsahovala nižší podíl živočišných proteinů a relativně více prosa. Vzhledem k tomu, že populace zázemí je zastoupena pouze souborem z Josefova, není možné s jistotou určit, zda se jednalo o jev charakteristický pro populaci zázemí. Svou roli mohla sehrát i relativní blízkost mikulčického centra. Hanáková a Stloukal (1966) vyslovili hypotézu o určité roli mužské populace Josefova například v obraně mikulčické sídelní aglomerace. Pokud je tato hypotéza správná, úzký vztah, případně i dočasné pobyty josefovských mužů v bohatém mikulčickém centru, mohly zlepšit kvalitu jejich stravy.

Specifickou otázkou zůstává konzumace ryb jako odraz postních regulí v raně křesťanské populaci Velké Moravy. Přestože křesťanské texty 9. století doporučují půst po poměrně značnou část roku (Bartoňková et al. 1971), izotopová data, jak už bylo uvedeno, neukazují na významnou roli ryb na populační úrovni. Zdá se tedy, že křesťanská víra neovlivnila potravní chování velkomoravské populace. Toto zapadá do celoevropského kontextu období před rokem 1000AD, kdy se konzumace ryb výrazně lišila v čase i prostoru. V některých oblastech byl pozorován nárůst konzumace ryb už u raných křesťanů (Barrett a Richards 2004; Rutgers et al. 2009), zatímco jinde i přes pokročilý stupeň christianizace k obdobnému zvýšení konzumace ryb nedošlo (Salamon et al. 2008).

Izotopová data souboru z 11. století ukazují, že v období po rozpadu Velké Moravy došlo k signifikantní proměně stravy sledované populace. Charakteristickým rysem pro toto období byla zvýšená konzumace prosa. V případě souboru mužů se také ukazuje, že došlo ke statisticky signifikantnímu snížení podílu živočišných proteinů ve stravě oproti souboru z velkomoravského zázemí. Strava mužů mladohradištního souboru se více podobala stravě žen, přestože pro hodnoty stabilních izotopů dusíku přetrvává malý, nicméně statisticky signifikantní rozdíl. V případě žen byla změna výživy mnohem mírnější než v případě mužů. Konzumace živočišných proteinů byla srovnatelná se souborem žen z velkomoravského zázemí. Přestože hodnoty stabilních izotopů uhlíku (ukazující na význam konzumace prosa) byly zvýšeny i v ženském souboru, tento rozdíl byl na rozdíl od mužů statisticky významný pouze ve srovnání s populací velkomoravských center, ale nikoliv velkomoravského zázemí. Pokles hodnot stabilních izotopů dusíku by mohl být teoreticky vysvětlen i poklesem hodnot na nižších úrovních potravního řetězce (viz diskuze k izotopovým hodnotám zvířat). V tom případě bychom však měli pozorovat obdobnou změnu izotopových hodnot u obou pohlaví. Existence signifikantního rozdílu pouze u mužů tedy ukazuje na reálnou změnu jejich potravního chování.

Při vysvětlení pozorovaných změn ve výživě je nutné vzít v potaz jak klimatické, tak socio-ekonomické faktory. Vrcholící klimatické optimum mohlo poskytovat vhodné podmínky právě k pěstování prosa, které je rostlinou teplomilnou a suchovzdornou (Konvalina et al. 2007; Moudrý 2005; Svoboda et al. 2003). Pokud ale vezmeme v úvahu pokles konzumace živočišných proteinů v případě mužů, jakož i archeobotanické nálezy z daného období, je třeba hledat možná vysvětlení i v socio-ekonomické sféře. Pokles konzumace proteinů totiž ukazuje na zchudnutí, či změnu socio-ekonomické struktury sledované populace. Strava mužů se přitom opět ukazuje být citlivějším ukazatelem socio-ekonomických podmínek než strava žen. Změnou socio-ekonomické struktury populace, lze vysvětlit i nárůst konzumace prosa. Zánikem bohatých velkomoravských center totiž mizí odbytiště pro luxusní plodiny, jako je pšenice. Populace se tak mohla obrátit k ne tolik prestižním, ale zato stabilní úrodu zajišťujícím produktům, jako je právě proso. Zánik velkomoravských center může být i alternativním vysvětlením zhoršené kvality stravy mužů.

Data menšího souboru, kde byla analyzována i minerální složka kostní tkáně, potvrzují závěry založené na analýze kolagenu: přímou konzumaci prosa variabilního významu ve velkomoravské populaci a i v širším středoevropském kontextu (McGlynn 2007; Reitsema 2012b; Reitsema et al. 2010) ojedinělý význam konzumace prosa v mladohradištním období. Na druhou stranu tento typ analýzy nepřinesl nové informace oproti analýze kolagenu, proto zůstal počet vzorkovaných jedinců omezen na třicet.

9.4.3 Lidské izotopové hodnoty souboru nedospělých

S pomocí intra-individuální strategie vzorkování (Herrscher 2003) bylo možné na základě rozdílu izotopových hodnot dusíku mezi vzorkem kosti a zubu ($\Delta^{15}N_{t\text{-}b}$) stanovit převažující charakter výživy (tzn. zda bylo dítě kojeno či odstaveno) u celkem 14 jedinců z Mikulčic (z celkového počtu 23) a 11 jedinců z Josefova (z celkem 18). V ostatních případech nebyl izotopový rozdíl mezi oběma vzorky dostatečný, a nebylo tedy možno převažující způsob výživy stanovit. Přestože hodnoty stabilních izotopů uhlíku by měly podle experimentální studie (Fuller et al. 2006b) reflektovat proces kojení a odstavení stejně jako stabilní izotopy dusíku a dokonce signalizovat raná stádia procesu odstavení, jejich využití v případě velkomoravské populace není možné. Izotopová data tohoto souboru jsou do značné míry ovlivněna konzumací prosa. Jeho využití jako doplňkové stravy v průběhu odstavení či sezónní variabilita v jeho konzumaci zcela překrývá efekt konzumace mateřského mléka.

Porovnání obou souborů s pomocí logistické regrese nepřineslo statisticky významné výsledky. To značí, že neexistovala norma v délce kojení, specifická pro populaci centra či populaci zázemí. Za biologicky významný rozdíl je však nutno považovat výrazně vyšší variabilitu v délce kojení, pozorovanou v souboru Mikulčic. První mikulčické děti byly odstaveny už v průběhu druhého roku života, zatímco jiné stále konzumovaly podstatné množství mateřského mléka ve věku 4-5 let. V souboru Josefova byly naproti tomu všechny děti mladší dvou let kojeny. Během třetího roku života pak pozorujeme prudký pokles izotopových hodnot ($\Delta^{15}N_{t\text{-}b}$), přičemž některé děti byly v tomto věku už zcela odstaveny. Vzhledem k nízkému počtu jedinců ve věkové kategorii 3-5 let však není možné přesně říci, kdy byl proces odstavení v populaci zázemí ukončen. Jako možné důvody pro vyšší variabilitu v délce kojení v populaci centra jsou zvažovány odlišné strategie odstavení v jednotlivých socio-ekonomických skupinách, přítomnost migrantů či vyšší tlak křesťanských regulí (Bartoňková et al. 1971). Je nicméně nutné zdůraznit, že zejména při relativně nízkém počtu analyzovaných vzorků mohly být pozorované trendy do značné míry ovlivněny řadou individuálně působících faktorů (např. zdravotní stav matky či dítěte) které jsou v archeologickém kontextu nezachytitelné (Mulder-Sibanda a Sibanda-Mulder 1999; Simondon et al. 2001).

Porovnání izotopových hodnot souboru nedospělých se souborem žen (jako potenciálních matek) ukazuje, že intra-individuální strategie vzorkování byla zvolena správně. Vysoká variabilita izotopových dat souboru žen totiž prakticky znemožňuje využití rutině prováděné průřezové strategie, kdy je pokles izotopových hodnot nedospělých na úroveň dospělých považován za znak odstavení. Variabilita souboru žen je zejména v Mikulčicích natolik vysoká, že velká část dětí kojených matkami s nižšími izotopovými hodnotami by mohla být mylně považována za odstavené.

Nicméně i zvolená strategie vzorkování má svá omezení. Je to v první řadě skutečnost, že u vysokého procenta jedinců není možné dominantní způsob výživy určit vzhledem k nedostatečnému izotopovému rozdílu ($\Delta^{15}N_{t\text{-}b}$). Dále je to zejména fakt, že studie je provedena na souboru dětí, které nepřežily období dětství, což může významně zkreslit reprezentativnost dat (Beaumont et al. 2015; Wood et al. 1992). Vzhledem k nemožnosti odhadu pohlaví u nedospělých jedinců není také možné porovnat strategii odstavení mezi chlapci a dívkami, která se v řadě populací liší (Eerkens a Bartelink 2013; Jayachandran a Kuziemko 2011). Tato část studie byla provedena v letech 2011-2012. Díky rychlému rozvoji hmotnostní spektrometrie v posledních letech bude s pomocí metody sériových řezů dentinu (Beaumont et al. 2013; 2015; Henderson et al. 2014) v budoucnu možné studovat proces odstavení ve sledované populaci mnohem detailněji.

9.5 Vztah výživy a ukazatelů zdravotního stavu ve velkomoravské populaci

Základní testovanou hypotézou v této části práce bylo, že monotónní strava založená především na obilovinách s nízkým podílem živočišných proteinů vede ke zhoršení zdravotního stavu (Armelagos a Cohen 1984; Bennike 1985; Bocquet-Appel et al. 2008; Brinch a Moller-Christensen 1949; El-Najjar 1976; 1982; El-Najjar et al. 1975; 1976; Hillson 1996; Larsen 1997; Larsen et al. 1995; Lukacs 1992; Milner 1984; Moore a Corbett 1971; 1973; 1975; Powell 1985; Sledzik a Moore-Jansen 1991). U jedinců s nižším podílem živočišných proteinů ve stravě tak byl očekáván vyšší výskyt dentálních patologií a vyšší výskyt nespecifických stresových indikátorů. Alternativní hypotéza pak byla založena na premise osteologického paradoxu (Wood et al. 1992), kdy naopak kvalitní strava prodlužuje dobu přežití a poskytuje tak dostatek času pro vývoj patologických změn.

U všech osteologických znaků bylo na prvním místě ověřeno, zda existuje signifikantní vztah mezi těmito indikátory a demografickými daty (věk a pohlaví). Podle výsledku této analýzy a typu dat pak byla zvolena odpovídající statistická metoda pro ověření vztahu mezi izotopovými hodnotami a osteologickými znaky.

Výsledky statistického vyhodnocení doložily signifikantní vztah mezi charakterem stravy a výskytem dentálních patologií. Zejména v souboru žen byl nízký podíl živočišných proteinů ve stravě spojen se zvýšenou kazivostí a vyšším výskytem periodontitidy. Obdobný, přestože nikoliv tak jednoznačný, trend byl pozorován i v případě kazivosti v souboru mužů. Tyto výsledky jsou ve shodě s výše zmíněnou hypotézou. Mnohem obtížněji vysvětlitelný je signifikantní vztah mezi intenzitou kazivosti, stupněm zubní abraze a hodnotami stabilních izotopů uhlíku, pozorovaný v souboru mužů. Jejich izotopové hodnoty ukazují, že muži konzumující větší množství prosa měli méně zubních kazů a méně abradovaný chrup. Hypoteticky může vysvětlení souviset s texturou stravy. Proso bylo pravděpodobně konzumováno převážně ve formě prosné kaše (Beranová 2005). Jeho zvýšená konzumace tedy může naznačovat preferenci jemné kašovité stravy, která vede k nižší zubní abrazi a tím i nižší kazivosti zubů (Hillson 2005; Larsen 1997). Proti tomuto vysvětlení však hovoří fakt, že u žen obdobný trend pozorován nebyl.

Pro nespecifické stresové indikátory: výšku postavy a výskyt *cirbra orbitalia* nebyl nalezen signifikantní vliv výživy. Vysvětlením může být jejich multifaktoriální etiologie, kdy kvalita stravy je pouze jedním z potenciálních faktorů (Walker et al. 2009; Wapler et al. 2004) vzniku lézí. V případě výšky postavy pak může hrát roli i fakt, že výška reflektuje životní podmínky v období růstu a vývoje (Bogin 1999), zatímco stabilní izotopy odrážejí výživu v posledních letech života (Hedges et al. 2007).

V případě souboru nedospělých jedinců nebylo, jak už bylo uvedeno výše, srovnání izotopových a osteologických dat na individuální úrovni možné z důvodu nízkého počtu jedinců, u nich byly získány izotopové hodnoty. Osteologické zhodnocení zdravotního stavu ve vztahu k výživě tedy spočívalo v ověření hypotézy, že rozdíly v délce kojení mezi populací centra a zázemí (tj. vyšší variabilita délky kojení v populaci centra) se odpovídajícím způsobem odrazí v profilech morbidity obou populačních skupin. Hypotézou založenou na izotopových výsledcích tedy bylo, že v populaci centra bude výskyt nespecifických stresových indikátorů rovnoměrně rozdělen do jednotlivých věkových skupin, zatímco v populaci zázemí bude pozorován nárůst nemocnosti a úmrtnosti v průběhu třetího roku života. Výsledky logistické regrese však neprokázaly existenci rozdílů ve výskytu nespecifických stresových indikátorů mezi souborem centra a zázemí a nelišilo se ani rozložení nemocnosti ve vztahu k věku. Rovněž studie růstu neprokázala signifikantní rozdíly mezi oběma skupinami pro většinu rozměrů, přestože nedospělí ze zázemí dosahovali ve všech případech mírně menších rozměrů.

Přestože studií tohoto typu doposud není mnoho, jejich dosavadní výsledky naznačují, že úroveň biologického stresu byla v rámci archeologických populací výrazně variabilní (Howcroft et al. 2012; Mays 2010; Pearson et al. 2010; Schurr 1997). Velkomoravská populace přitom patří mezi ty, kde nebyl nalezen kauzální vztah mezi délkou kojení a nemocností. Zdá se tedy, že většina populace čerpala ze zdravotních benefitů dlouhodobého kojení. Je však nutné zmínit, že zvolená strategie vzorkování umožňuje detekovat pouze významný pokles v příjmu mateřského mléka a nikoliv zavedení prvních výživových přídavků, které mohly být z hlediska biologického rizika infekce mnohem významnějším faktorem (např. Newman 1995). Toto spolu s metodologickými omezeními izotopové analýzy (viz. výše) mohlo přispět k nezachycení potenciálně existujícího vztahu. Jak už bylo uvedeno výše, dalším krokem v této oblasti by mělo být využití metodologie sériových řezů dentinu, které umožní sledovat proces odstavení detailněji.

9.6 Hlavní závěry

Výsledky izotopové analýzy ukazují na pokročilou socio-ekonomickou stratifikaci velkomoravské společnosti, která se projevovala rozdílným přístupem jednotlivých skupin populace k živočišným proteinům. Obyvatelé center měli v průměru lepší přístup k živočišným proteinům než obyvatelé zázemí. V rámci souboru mužů z populace center pak socio-ekonomické postavení jedince (odvozené na základě hrobové výbavy) mělo také signifikantní vliv na konzumaci této složky potravy. V případě žen jsme obdobný trend nepozorovali. Izotopová data jak souboru lidí, tak i zvířat (zejména prasat) ukazují na to, že i přes bezprecedentní rozvoj velkomoravských center byl jejich stupeň urbanizace relativně nízký – neprojevoval se ani zhoršením kvality výživy příslušníků nižších socio-ekonomických skupin, ani změnou izotopových hodnot prasat, která by signalizovala přechod způsobu chovu od extenzivního k městskému.

Byly pozorovány signifikantní změny ve výživě mezi velkomoravským a mladohradištním souborem, které spočívaly zejména ve vyšší konzumaci prosa a v případě mužů i ve snížení konzumace živočišných proteinů. I tyto výsledky naznačují, že mužské potravní chování bylo senzitivnější na změny socio-ekonomických podmínek než v případě žen, jejichž strava byla více stabilní napříč socio-ekonomickými skupinami i mezi jednotlivými obdobími.

Přestože výživové faktory byly mnoha autory označovány za pravděpodobnou příčinu pozorovaných změn zdravotního stavu na populační úrovni (např. Larsen 1997) tato práce představuje jeden z prvních pokusů o propojení izotopových dat a osteologických markerů zdravotního stavu na individuální úrovni. Přestože prokázaný vztah mezi charakterem stravy a stavem chrupu je třeba dále ověřit na početnějším souboru, tento výsledek ukazuje na vysoký potenciál izotopové analýzy výživy ve vysvětlení inter- a intrapopulačních rozdílů přinejmenším v některých aspektech zdravotního stavu.

Soubor nedospělých jedinců vykazuje vysokou variabilitu v délce kojení, zejména v populaci mikulčického centra. To ukazuje, že zřejmě neexistovala pouze jedna závazná forma, která by byla plošně uplatňována napříč velkomoravskou populací. Osteologické vyhodnocení souboru ukazuje, že aplikované strategie kojení a odstavení neovlivnily signifikantně riziko biologického stresu, kterému populační skupiny centra a zázemí musely čelit.

10 RÉSUMÉ (FRENCH SUMMARY)

10.1 Introduction

La période des IXe et Xe siècles est cruciale dans le contexte de l'Europe centrale pour le développement de la société. Les changements significatifs dans les domaines sociaux, politiques et religieux ont conduit à la création des piliers fondamentaux de la société d'Europe centrale sous sa forme actuelle. L'empire de la Grande-Moravie représentait sans aucun doute la force motrice de ce processus (Berend et al. 2013). Le développement de la Grande-Moravie a été rendu possible par les conditions favorables de l'optimum climatique naissant, conduisant à l'augmentation de la production agricole qui a permis la croissance de la population (Brázdil et al. 2005 ; Poláček 2001).

Bien que les débats sur la question du « statut d'État » soient toujours en cours (par ex. Macháček 2012 ; Štefan 2011), le processus de formation de cette structure d'État ou plutôt de proto-État a sans aucun doute influencé les conditions de vie de la population. Les sources archéologiques et écrites montrent l'importance de la stratification sociale et de propriété de la société de la Grande-Moravie. D'autres changements significatifs du style de vie ont probablement accompagné l'adoption du christianisme qui se répand dans la zone concernée depuis le début du IXe siècle. Bien que limitée surtout au début au petit groupe des couches d'élite de la société, sa propagation est supposée au IXe siècle parmi les groupes socio-économiques inférieurs et en dehors des principaux centres. Une caractéristique associée à la formation de la Grande-Moravie a également été la mise en place et le développement de vastes centres, généralement situés dans des endroits élevés des plaines inondables des principaux cours d'eau (par ex. Poláček 2008b). Il est supposé que ces centres n'étaient pas pleinement autarciques au niveau alimentaire. Bien que des recherches récentes montrent l'existence de terres cultivables (Látková 2015) et l'implication probable d'une partie de la population des centres dans la production agricole, le rôle de l'approvisionnement en produits alimentaires et matières premières clés semble irremplaçable. Cela est confirmé par la forte accumulation d'agglomérations et de nécropoles à proximité des principaux centres (Dresler et Macháček 2008 ; Poláček 2008b).

Le développement de la Grande-Moravie s'est achevé au début du Xe siècle, lorsque la crise politique et l'attaque militaire qui a suivi ont entraîné la disparition des agglomérations centrales et la diminution globale de la population et de la densité de peuplement dans la région concernée. Le changement climatique observé durant cette période a également pu jouer un rôle négatif. Les principaux centres de la Grande-Moravie ont pu faire face à des inondations, s'étendant durant la période précédente, des positions élevées vers les zones des basses plaines inondables (Macháček 2013b).

Les premiers signes d’une reprise de la société sur les territoires de l'empire disparu de la Grande-Moravie sont déjà observés dans les dernières décennies du X^{e} siècle (Macháček et Videman 2013), le renouvellement de la société et des structures résidentielles a été achevé au XI^{e} siècle (« late Hillfort période »), avec la contribution possible de l'optimum climatique (Svoboda et al. 2003)

Ces circonstances historiques uniques permettent d'étudier les différents aspects du comportement humain et de l'état sanitaire dans le contexte unique des changements sociaux, économiques et religieux rapides et plusieurs générations d'anthropologues tchèques se concentrent avec intérêt sur l'étude de la population de la Grande-Moravie (par ex. Bigoni et al. 2013 ; Garcin et al. 2010 ; Hanáková et Stloukal 1987 ; Havelková et al. 2010 ; Sládek et al. 2015 ; Stloukal 1970 ; Stloukal et Vyhnánek 1976 ; Stránská et al. 2015 ; Velemínský et Poláček 2008). L'analyse isotopique de l'alimentation et sa relation avec l'état sanitaire de la population concernée reste encore un des sujets, à quelques exceptions près (Halffman et Velemínský 2015 ; Smrčka et al. 2008), n'ayant pas fait l'objet d'une attention systématique.

Le principe fondamental de l'analyse isotopique de l'alimentation est que le signal isotopique des aliments consommés s’enregistre dans les tissus du consommateur, lors de l'application globale des processus géochimiques. L’analyse conjointe des valeurs isotopiques du carbone ($\delta^{13}C$) et de l'azote ($\delta^{15}N$) est utilisée dans l’étude de l'alimentation. Les valeurs des isotopes stables du carbone nous permettent d'identifier certaines caractéristiques fondamentales de l'écosystème au sein duquel l'individu a acquis ses sources de nourriture : elles permettent de faire la distinction entre le milieu terrestre et marin et d'identifier la proportion des plantes C_3 et C_4 dans le régime alimentaire de l'individu. Les isotopes stables de l'azote permettent de déterminer la position de l'organisme dans la chaîne alimentaire. Concernant l'homme (espèce omnivore), ils nous informent sur l'importance des protéines animales dans l'alimentation. Bien que les valeurs isotopiques des écosystèmes d'eau douce soient très variables, l’analyse conjointe des valeurs isotopiques du carbone et de l'azote peut aider à répondre à la question de la consommation de poissons d'eau douce. L'analyse isotopique du soufre ($\delta^{34}S$) peut éventuellement apporter des précisions à cette question (mais uniquement sous certaines conditions) (Ambrose et Norr 1993 ; DeNiro et Epstein 1978 ; 1981 ; Lee-Thorp 2008 ; Minagawa et Wada 1984 ; Nehlich et al. 2010 ; Richards et al. 2001 ; Schoeninger et DeNiro 1984).

L'analyse isotopique du collagène qui est la base de cette étude est couramment utilisée pour la reconstruction de l'alimentation (par ex. Katzenberg 2007 ; Schwarcz et Schoeninger 2012). Une autre possibilité est l'analyse de la partie minérale du tissu osseux qui peut aider à résoudre les questions spécifiques, par ex. la consommation de plantes en C_4 dans de faibles quantités (Harrison et Katzenberg 2003). Son utilisation est toutefois compliquée par l'estimation problématique de l'état de conservation de l'échantillon (Zazzo et al. 2004).

Outre la reconstruction générale de l'alimentation, il est possible d'utiliser l'analyse isotopique pour résoudre des questions spécifiques. Le plus souvent – même dans le cas de cette étude – il s'agit de la détermination de la durée d'allaitement dans les populations du passé. Cela est possible grâce à l'augmentation du niveau trophique qui se produit au cours de la consommation du lait maternel et qui se traduit par l'augmentation des valeurs isotopiques du carbone et en particulier de l'azote (Fogel et al. 1989 ; Fuller et al. 2006b). La tendance actuelle de l'analyse isotopique, qui a été utilisée également dans cette étude, est ladite stratégie intra-individuelle de l'échantillonnage (Beaumont et al. 2013 ; Eerkens et al. 2011 ; Henderson et al. 2014 ; Herrscher 2003) avec l'utilisation des tissus dentaires dont le signal isotopique, en l'absence de remodelage (Balasse et al. 1999 ; Richards et al. 2002) diffère de l'information temporelle enregistrée dans le tissu osseux. La comparaison des valeurs isotopiques entre les os (contenant des informations d'une période plus longue avant la mort) et la racine dentaire en formation (portant les informations de la période précédant immédiatement le décès) a été appliquée à un groupe de sujets immatures âgés de moins de 6 ans et cela a permis de déterminer si un enfant a connu une baisse significative de la consommation du lait maternel au cours de sa vie (Herrscher 2003).

L'importance de la reconstruction de l'alimentation des populations du passé est soutenue par le fait que l'alimentation est l'un des principaux déterminants de la santé, non seulement l'apport énergétique suffisant mais également la variabilité des aliments (Hockett et Haws 2003 ; Kant et Graubard 2005 ; Kant et al. 1993 ; Lee et al. 2011). Les recherches de l'état sanitaire des populations archéologiques indiquent que l'un des principaux facteurs qui menaçait l'état de santé des populations du passé était l'alimentation monotone riche en céréales. L'exemple le plus connu est évidemment la période d'intensification de la culture du maïs sur le continent américain (Kealhofer et Baker 1996 ;

Knudson et Stojanowski 2008 ; Larsen 1994 ; 2001 ; Larsen et Milner 1994 ; Steckel et Rose 2002). Étant donné que la qualité de l'alimentation dans les premières années de la vie influe de façon significative sur l'état sanitaire de l'individu pendant cette période et sur le long terme (Demmelmair et al. 2006 ; Haines et Kintner 2008 ; McDade 2005 ; Palou et Pico 2009), l'étude des relations entre la durée de l'allaitement maternel et l'état de santé de la population concernée revêt une importance particulière. La comparaison des indicateurs de l'état sanitaire et des indicateurs d'isotopes de l'alimentation au niveau individuel, à quelques exceptions près (Yoder 2006), n'a pas fait l'objet d'une attention systématique.

10.2 Objectifs de l'étude

Les hypothèses vérifiées dans le cadre de la présente étude peuvent être divisées en plusieurs domaines fondamentaux :

1) Le premier est l'impact des facteurs socio-économiques et religieux sur l'alimentation des différents groupes de la population de la Grande-Moravie. Il est à supposer que la population des centres et les couches socio-économiques supérieures ont une consommation plus élevée de protéines animales. D'autre part, si l'urbanisation des centres de la Grande-Moravie a atteint un certain niveau, il est possible d'envisager une augmentation de la variabilité de l'alimentation dans ces groupes, conditionnée par la création de la couche pauvre de la population urbaine (Koepke et Baten 2005 ; 2008 ; Komlos 1998 ; Larsen 1997) qui se caractérise par une faible proportion de protéines animales dans l'alimentation. Les coutumes religieuses entraînent la croissance de la consommation des poissons d'eau douce ou de mer durant le jeûne (Barrett et Richards 2004 ; Müldner et al. 2009 ; Rutgers et al. 2009). Compte tenu de la propagation du christianisme des groupes d'élite de la population vers les couches socio-économiques inférieures et des centres vers l'arrière-pays (Poláček 2008b), on peut supposer une plus grande consommation de poissons chez les habitants des centres et les individus ayant atteint un niveau socio-économique supérieur.

2) Les facteurs mentionnés ci-dessus ont sans aucun doute influencé non seulement l'alimentation des adultes mais également celle des sujets immatures, y compris la durée de l'allaitement maternel. En raison des exigences financières et matérielles de ce type d'étude, les questions vérifiées ont été limitées à la comparaison des tendances dans l'alimentation des nourrissons et des jeunes enfants entre les centres et l'arrière-pays.

3) Un autre thème est l'étude des tendances diachroniques de l'alimentation en relation avec la disparition de l'empire de la Grande-Moravie et le renouvellement ultérieur de la société au cours du XI^{e} siècle. Durant la phase finale de l'existence et la disparition de la Grande-Moravie (Macháček et al. 2014), la détérioration de la qualité de l'alimentation de la population des centres de la Grande-Moravie est supposée, suite à l'appauvrissement de la population et l'effondrement de la redistribution des denrées alimentaires. Au XI^{e} siècle (« late Hillfort période »), l'augmentation de la qualité des aliments est de nouveau attendue en raison de l'adaptation de la population aux nouvelles conditions climatiques et sociales (Hladík 2014 ; Lozny 2004). La disparition des grands centres ont pu jouer un rôle positif car les ménages ruraux pouvaient obtenir plus de denrées alimentaires de qualité sans la nécessité d'approvisionnement des vastes centres habités (Koepke 2002 ; Komlos 1985 ; 1998).

4) En raison de l'impact de la qualité de l'alimentation sur la santé des individus, des différences dans l'état de santé peuvent être envisagées. Considérant, la part des protéines animales dans l'alimentation comme un indicateur de la traçabilité de la qualité de l'alimentation, l'utilisation des isotopes stables revêt ici un intérêt particulier.

5) L'obtention des valeurs référentielles caractérisant les valeurs de l'écosystème local fait également partie de l'analyse isotopique de l'alimentation. Un ensemble d'os d'animaux est analysé à cet effet. Cet ensemble a été choisi afin de permettre la vérification maximale de l'effet des facteurs potentiels pouvant influencer les valeurs isotopiques sur la base des chaînes alimentaires. Nous avons vérifié les hypothèses suivantes : a) Les pratiques d'élevage et d'agriculture influencent les valeurs isotopiques des animaux domestiques par rapport aux animaux sauvages. b) L'environnement spécifique des plaines inondables influence les valeurs isotopiques des animaux élevés à proximité des centres de la Grande-Moravie par rapport aux animaux élevés dans l'arrière-pays. c) Les valeurs isotopiques des porcs élevés à proximité des centres sont influencées par l'urbanisation en cours (Hammond et O'Connor 2013). C'est la raison pour laquelle elles diffèrent des valeurs des ruminants domestiques et des porcs élevés dans l'arrière-pays. d) Le changement des conditions climatiques et le développement des pratiques agricoles ont influencé les valeurs isotopiques du groupe d'animaux de la période « late Hillfort » du XI^{e} siècle par rapport aux animaux de la période de la Grande-Moravie.

6) Bien que cette étude soit principalement basée sur l'analyse des échantillons de collagène, le potentiel d'analyse du composant minéral du tissu osseux sur un ensemble d'os humains sélectionné a été vérifié. Le potentiel de l'analyse isotopique du soufre a également été vérifié sur l'ensemble des os d'animaux.

10.3 Matériel et méthodes

Les données isotopiques de cinq groupes de squelettes datant de la période de la Grande-Moravie (IX^{e} – début du X^{e} siècle) et de la période « late Hillfort » (XI^{e} siècle) ont été utilisées pour tester les hypothèses mentionnées ci-dessus. Les groupes étudiés peuvent être divisés selon les critères socio-économiques et diachroniques comme suit : 1) « les centres de la Grande-Moravie », représentés par les groupes de Mikulčice - Château (N=70) et Pohansko – Severovýchodní předhradí (N=56), 2) « l'arrière-pays de la Grande-Moravie », représenté par les sépultures « Great moravian » de la nécropole de Josefov (voir « Josefov I » ; N=32) et 3) « le groupe de la période late Hillfort » sans les critères socio-économiques (N=31), provenant des nécropoles petites ou incomplètes de Louky od Břeclavska et de Josefov – phase de la période late Hillfort (Josefov II). Concernant les sujets immatures échantillonnés pour l'analyse de l'allaitement et sevrage, l'étude a été limitée à la comparaison des populations des centres de la Grande-Moravie (Mikulčice – Château, N=23) et de l'arrière-pays (Josefov, N=18). Les valeurs isotopiques de la partie minérale du tissu osseux ont été mesurées dans un échantillon de trente individus des localités de Mikulčice (N=10), Josefov I (N=10) et Louky od Břeclavska (N=10).

Le groupe comparatif des animaux devait représenter les trois principaux groupes mentionnés ci-dessus. A l'exception des centres de la Grande-Moravie (Mikulčice N=42, Pohansko N=10), il s'est avéré impossible d'obtenir des quantités suffisantes d'ossements animaux provenant de ces localités. L'ensemble d'os d'animaux de Josefov (N=3) a donc été complété par du matériel provenant de la proche agglomération de Mutěnice – Zbrod de la Grande-Moravie (N=15). Le groupe de la période late Hillfort est représenté par du matériel de cette phase de l'agglomération de Kostice – Zadní Hrůd (N=10). Les valeurs des isotopes stables du soufre ont été mesurées sur un petit groupe de 22 animaux de Mikulčice (N=18) et de Pohansko (N=4).

Pour différentes raisons, le traitement ostéologique pour l'analyse des relations entre l'alimentation et l'état de santé a été limité aux groupes de Mikulčice, représentant les centres de la Grande-Moravie, et Josefov pour l'arrière-pays de la Grande-Moravie.

L'analyse ostéologique et isotopique a été réalisée sur le même échantillon d’adultes. Compte du faible nombre de sujets immatures dont les valeurs isotopiques ont été mesurées, les analyses statistiques des indicateurs ostéologiques ont été impossibles. C'est la raison pour laquelle les groupes ont été étendus à 144 individus de Mikulčice et 158 individus de l'arrière-pays et compt tenu du nombre limité d'individus dans cette catégorie d'âge découverts à Josefov, le groupe a été complété des sujets issus de la localité de Prušánky I.

Les échantillons de collagène ont été préparés avec la méthode de Longin (1971) modifiée par Bocherens (1992). Concernant les adultes, les échantillons d'os proviennent des côtes, des mains ou des pieds (les phalanges en particulier). Pour les immatures, les échantillons ont été prélevés dans la base de la mandibule et les échantillons de la dentine proviennent des racines dentaires en formation. Certaines dents ont été sélectionnées en fonction de l'âge de l'individu, notamment les premières et deuxièmes molaires déciduales. Les échantillons pour l’analyse de la fraction minérale du tissu osseux ont été préparés selon la méthode de Garvie-Lok et al. (2004) avec la modification apportée par Salesse et al. (2013) en utilisant le reste de matériel osseux après l'extraction du collagène. Les mesures isotopiques ont été réalisées à l'aide des analyseurs *Europa Scientific EA elemental analyzer* et *Europa Scientific 20-20 IRMS* sous la direction technique de la société Iso-Analytical Limited, Crewe du Royaume-Uni.

L'estimation de l'âge et du sexe des adultes a été réalisée dans les groupes des localités de Mikulčice, Josefov I et II et Prušánky I à l'aide des méthodes suivantes : Brůžek et Velemínský (2008), Murail et al. (2005), Ferembach et al. (1980) et Schmitt (2005 et 2008). Concernant les localités de Pohansko – Severovýchodní předhradí et Louky od Břeclavska, les données démographiques fondamentales ont été fournies par une équipe de Vladimír Sládek. L'âge des sujets immatures a été évalué à l'aide des méthodes de Liversidge et al. (1998), et de Moorrees et al. (1963) et Smith (1991) et Scheuer et Black (2000) et Stloukal et Hanáková (1978) le cas échéant. Les indicateurs de l'état de santé chez les adultes concernent la présence de *cribra orbitalia* (Nathan et Haas 1966), de caries dentaires et de leur intensité (ICE) (Stloukal et Vyhnánek 1976), de parodontite et de lésions périapicales. L'abrasion dentaire a été évaluée selon la méthode de Scott (1979). La stature des individus a été calculée à partir de la longueur du fémur (M1 selon Bräuer 1988). Dans le cas des immatures, a été évaluée la présence de lésions endocrâniennes en utilisant les critères de Lewis (2004) et la présence de *cribra orbitalia* a été côtée comme chez les adultes. L'utilisation de la méthode de Nathan et Haas (1966) a permis d'évaluer la présence d'hyperostose porotique sur le frontal, les pariétaux et l'occipital. La longueur de la diaphyse, les diamètres antéro-postérieur et médio-latéral du centre de la diaphyse du fémur, du tibia et de l'humérus (Mays et al. 2009) ont également été mesurés.

10.4 Résultats et discussions

10.4.1 Les valeurs isotopiques du groupe d'animaux

Le groupe d'animaux sauvages et la majorité des échantillons des bovins, moutons/chèvres et porcs domestiques ont un signal isotopique typique d'un écosystème en C_3, à l'exception d'un échantillon de bovins (MUTF10) dont la valeur indiquerait un rôle relativement important des plantes en C_4 (millet) dans son régime alimentaire. Plusieurs autres échantillons indiquent des valeurs d'isotopes stables du carbone autour de -19‰, ce qui n'exclut pas le rôle du millet comme aliment complémentaire. Les chiens et la volaille représentent un groupe d'animaux domestiques clairement séparé au niveau des valeurs isotopiques de l'azote et du carbone. Leurs valeurs isotopiques indiquent clairement la consommation de plantes en C_4. Ces valeurs ne reflètent pas uniquement la place de ces espèces dans la chaîne alimentaire mais également leur relation étroite avec l'homme. Les chiens et la volaille, élevés à proximité des habitations, ont pu consommer des restes de nourriture humaine, des déchets et des excréments. Par rapport aux autres espèces, leur alimentation reflète l'alimentation humaine (Guiry 2013; Reitsema et al. 2013). Dans ce contexte, il est intéressant de constater que les valeurs isotopiques des porcs des centres correspondent aux valeurs des ruminants domestiques. Elles se distinguent de la tendance observée chez les chiens et la volaille (Hammond et O'Connor 2013). Ce fait démontre que malgré le degré de développement atteint dans les centres de la Grande-Moravie, le degré d'urbanisation demeure relativement faible et permet l'élevage extensif du porc. Les analyses statistiques n'ont démontré aucune différence significative entre les espèces sauvages et les espèces domestiquées (à l'exception des chiens et de la volaille) ni entre les animaux domestiques/consommés dans les centres et l'arrière-pays. Cela indique que les pratiques économiques ou les conditions naturelles spécifiques dans les plaines inondables ne se reflétent pas de façon significative sur les valeurs isotopiques des animaux. L'unique facteur statistique important est le temps, illustrée par des valeurs inférieures des rapports isotopiques de l'azote des animaux de la période late Hillfort par rapport aux animaux de la période de la Grande-Moravie. L'inclusion ou l'exclusion du groupe des chiens et de la volaille n'influe pas sur ces résultats. Cependant, il est probable que la différence observée soit due principalement aux valeurs isotopiques inférieures des deux échantillons de porcs domestiques. Compte tenu du faible nombre de porcs échantillonnés et de la taille globale du groupe d'animaux de la période Late Hillfort, il est impossible de déterminer s'il s'agit uniquement d'un effet résultant de la petite taille du groupe ou d'un réel des changements dans le type d'élevage des porcs. Cependant, il est important de considérer cette particularité lors de l'évaluation des changements diachroniques du régime alimentaire des humains.

Les valeurs du groupe de poissons indiquent une variabilité similaire comparativement aux valeurs typiques pour les espèces d'eau douce européennes (Fuller et al. 2012 ; Reitsema et al. 2013 ; Vika et Theodoropoulou 2012). A cet égard, il est important de noter que seules des valeurs du groupe de poissons significativement différentes du groupe d'animaux terrestres permet d'en démontrer leur consommation à partir des valeurs isotopiques de l'azote et du carbone (Reitsema et al. 2013). Cependant, les valeurs isotopiques de deux échantillons de poissons (MIKF40 a MIKF42) sont proches des valeurs des animaux terrestres. Il est donc impossible d'exclure – en particulier lors d'une préférence individuelle d'espèces particulières – à partir des valeurs isotopiques humaines la consommation de poissons. C'est la raison pour laquelle nous avons décidé d'analyser les isotopes stables du soufre. Cependant, cette analyse ne peut être appliquée lors de la reconstruction de la consommation de poissons d'eau douce que dans certains cas (lorsque les valeurs de l'environnement terrestre et aquatique diffèrent) et cela est difficilement prévisible malgré la connaissance de la géologie locale (Privat et al. 2007). Par conséquent, une étude pilote a été réalisée sur un ensemble de poissons (N=7) et d'animaux terrestres (N=15). Malheureusement, les résultats de cette étude ont montré l'inopportunité totale de cette analyse dans le contexte de la Grande-Moravie. En fait, les valeurs isotopiques des poissons ont montré une grande variabilité avec deux groupes de valeurs extrêmes. Les valeurs de tous les animaux terrestres se situent entre ces extrêmes. Les causes possibles de ce phénomène seraient les modifications diagénétiques envisagées, l'utilisation de cours d'eau et réservoirs différents ou la variabilité des valeurs isotopiques dans les plaines inondables (Privat et al. 2007 ; Trembaczowski 2011 ; Ward et al. 1999).

10.4.2 Les valeurs isotopiques humaines des adultes

Les données isotopiques du groupe de la Grande-Moravie sont caractéristiques d'une alimentation basée sur des organismes terrestres, avec une part importante de plantes en C_4

(millet). La comparaison avec les valeurs isotopiques des animaux indique qu'il s'agissait de la consommation directe du millet (par ex. sous forme de bouillie de millet) et non pas celle du lait et de la viande des animaux nourris à base de millet. La combinaison des valeurs du carbone et de l'azote et leur comparaison avec le groupe d'animaux indiquent également que les poissons n'étaient pas une composante importante de l'alimentation de la population. Cependant, nous ne pouvons pas exclure leur consommation accrue chez certains individus.

Dans le contexte de l'Europe centrale, notre groupe partage donc des similitudes avec d’autres groupes des populations slaves (Lightfoot et al. 2012 ; Reitsema 2012 ; Reitsema et al. 2010) confirmant l'hypothèse d’un intérêt particulier de l'ethnie slave pour cette céréale (Barford 2001).

La comparaison de l'alimentation entre les groupes provenant des centres de la Grande-Moravie (Mikulčice *versus* Pohansko) n'indique pas des différences statistiquement significatives. Il semble donc probable que malgré le niveau hiérarchique sans doute inférieur des structures étatiques de la Grande-Moravie et l'appauvrissement évident de la population et le déclin attendu du système de distribution des denrées alimentaires vers la fin de la période de la Grande-Moravie (Macháček et al. 2014), les individus de la population du Pohansko aient réussi à maintenir une qualité de leur alimentation similaire à celle que nous observons dans le groupe de Mikulčice. Ceci est valable au minimum pour les paramètres observables à l'aide de l'analyse isotopique, notamment la proportion de protéines animales dans l'alimentation. Une explication possible est apportée par l'analyse archéozoologique en cours du matériel de Pohansko (Dresler et Macháček, communication orale) qui indique la proportion anormalement élevée d’animaux sauvages issus de la chasse, remplaçant ainsi les protéines provenant des espèces domestiques.

Les facteurs biologiques (sexe et âge au décès) n'ont pas influencé de façon significative le régime alimentaire des groupes des centres de la Grande-Moravie. Les deux groupes partagent la même tendance en termes d'alimentation et de statut socio-économique de l'individu. Il s'agit d'un impact statistiquement significatif du statut socio-économique sur la proportion des protéines animales dans l'alimentation des hommes. Les hommes enterrés avec de riches objets funéraires (dans le cas de Mikulčice) ou dans des tombes à structures (dans le cas de Pohansko) ont montré une plus grande proportion de protéines animales dans l'alimentation que les hommes enterrés sans ou avec simple objets funéraires (Mikulčice) ou en pleine terre (Pohansko).

Le groupe de femmes n'indique aucune relation similaire. Une des possibles raisons de ce phénomène serait la préférence culturellement conditionnée d'un sexe (Reitsema et Vercellotti 2012) ou le niveau différent de migration entre les sexes (Kjellström et al. 2009).

Du fait de l'absence de différences entre les deux groupes, les données de Mikulčice et de Pohansko ont été regroupées pour les autres analyses statistiques dans un groupe appelé « centres de la Grande-Moravie ». Lors de la comparaison avec le groupe de l'arrière-pays (localité de Josefov I), une différence statistique significative apparaît pour les valeurs isotopiques en azote, indiquant que la population de l'arrière-pays consommait en moyenne moins de protéines animales que les habitants des centres. Ces faits associées aux différences socio-économiques observées dans l'alimentation chez les populations des centres, indiquent une stratification socio-économique avancée de la société de la Grande-Moravie. Tous les habitants n'avaient pas un accès égal aux sources alimentaires. Le groupe de l'arrière-pays ne présentent pas de différences de pratiques alimentaires en fonction du statut socio-économique.En revanche, ici une différence statistiquement significative de l'alimentation apparaît entre les sexes. Celle des femmes contient moins de protéines animales et relativement plus de millet relativement aux sujets masculins. Etant donné que la population de l'arrière-pays est représentée uniquement par le groupe de Josefov, il est difficile de déterminer avec certitude s'il s'agissait d'un phénomène caractéristique de la population de l'arrière-pays. La proximité relative du centre de Mikulčice a pu avoir une certaine influence. Hanáková et Stloukal (1966) ont émis une hypothèse sur le possible rôle de la population masculine de Josefov dans la défense de l'agglomération de Mikulčice. Si cette hypothèse est juste, la relation étroite ou le séjour provisoire des hommes de Josefov dans le riche centre de Mikulčice, aurait pu améliorer la qualité de leur alimentation.

Une question spécifique est la consommation de poissons comme règle de jeûne dans la population chrétienne de la Grande-Moravie. Bien que les textes chrétiens du IX^{e} siècle recommandent le jeûne pour une partie relativement importante de l'année (Bartoňková et al. 1971), les données isotopiques n'indiquent pas le rôle important des poissons au niveau de la population. Par conséquent, il semble que la foi chrétienne n'ait pas influencé le comportement alimentaire de la population de la Grande-Moravie. Cela entre dans le cadre de la période avant l'année 1000 où la consommation de poissons diffère sensiblement dans le temps et l'espace. Dans certaines régions, l'augmentation de la consommation de poissons est observée chez les premiers chrétiens (Barrett et Richards 2004 ; Rutgers et al.

2009), alors qu'ailleurs l'augmentation de la consommation de poissons n'est pas enregistrée malgré le degré avancé de christianisation (Salamon et al. 2008).

Les données isotopiques du groupe du XI^{e} siècle indiquent que la période suivant l'effondrement de la Grande-Moravie a été marquée par un changement significatif de l'alimentation. La consommation accrue de millet est caractéristique pour cette période. Concernant le groupe des hommes, on assiste à la réduction significative de la proportion des protéines animales dans l'alimentation par rapport au groupe de l'arrière-pays de la Grande-Moravie. L'alimentation des hommes de la période late Hillfort ressemble plus à l'alimentation des femmes, malgré une petite différence statistiquement significative pour les valeurs isotopiques de l'azote. Concernant les femmes, le changement d'alimentation est beaucoup plus faible que chez les hommes. La consommation des protéines animales est comparable dans le groupe des femmes de l'arrière-pays de la Grande-Moravie. Bien que les valeurs isotopiques du carbone (indiquant l'importance de la consommation du millet) aient augmenté dans le groupe féminin, cette différence est significative uniquement par rapport à la population des centres de la Grande-Moravie mais non par rapport à celles de l'arrière-pays de la Grande-Moravie. La diminution des valeurs isotopiques de l'azote peut être théoriquement due à la baisse des valeurs des niveaux inférieurs de la chaîne alimentaire (voir débat sur les valeurs isotopiques des animaux). Dans ce cas, nous devrions observer des changements similaires des valeurs isotopiques chez les deux sexes. L'existence d'une différence significative uniquement chez les hommes indique un changement réel dans leur comportement alimentaire.

L'explication des changements observés dans l'alimentation doit prendre en considération les facteurs climatiques et socio-économiques. L'optimum climatique pouvait fournir des conditions appropriées pour la culture du millet, plante thermophile et résistante au climat sec (Konvalina et al. 2007 ; Moudrý 2005 ; Svoboda et al. 2003). Si nous prenons en considération la diminution de la consommation des protéines animales chez les hommes et les découvertes archéobotaniques de la période concernée, les explications possibles se trouvent également dans la sphère socio-économique. La baisse de la consommation des protéines indique l'appauvrissement ou le changement de structure socio-économique de la population. L'alimentation des hommes est de nouveau un indicateur plus sensible des conditions socio-économiques par rapport au régime alimentaire des femmes. Le changement de la structure socio-économique de la population peut expliquer l'augmentation de la consommation du millet. La disparition des riches centres de la Grande-Moravie entraîne la disparition sur le marché des céréales de « luxe » telles que le blé. La population pouvait se tourner vers des récoltes moins prestigieuses mais plus stables, comme le millet. La disparition des centres de la Grande-Moravie peut être une explication alternative à la détérioration de la qualité de l'alimentation des hommes.

L'analyse de la fraction minérale de quelques sujets a également confirmé les conclusions basées sur l'analyse du collagène: une importance variable de la consommation directe du millet à chez la population de la Grande-Moravie et dans le contexte de l'Europe centrale (McGlynn 2007 ; Reitsema 2012 ; Reitsema et al. 2010) et une consommation unique du millet dans la période late Hillfort. D'autre part, ce type d'analyse n'a apporté aucune nouvelle information par rapport à l'analyse du collagène, peut-être en raison du nombre limité d'individus échantillonnés (N=30).

10.4.3 Les valeurs isotopiques des sujets immatures

Grâce à une stratégie d'échantillonnage intra-individuelle (Herrscher 2003), il a été possible sur la base de la différence des valeurs isotopiques de l'azote entre l'échantillon de l'os et de la dent ($\Delta^{15}N_{t\text{-}b}$) de déterminer le caractère prédominant de l'alimentation (enfant allaité ou sevré) chez 14 individus de Mikulčice (sur un nombre total de 23) et 11 individus de Josefov (sur un nombre total de 18). Dans les autres cas, la différence isotopique entre les deux échantillons était insuffisante et il s'est avéré impossible de déterminer le type d'alimentation. Alors que les valeurs des isotopes stables du carbone doivent selon une étude expérimentale (Fuller et al. 2006b) refléter le processus de l'allaitement maternel et du sevrage, au même titre que les isotopes stables de l'azote, et signaler les premières étapes du processus de sevrage, leur utilisation dans le cas de la population de la Grande-Moravie s'est avérée impossible. Les données isotopiques de ce groupe sont largement influencées par la consommation du millet. Son utilisation comme complément alimentaire durant le sevrage ou la variabilité saisonnière de sa consommation recouvre complètement l'effet de la consommation du lait maternel.

La comparaison des deux groupes à l'aide de la régression logistique n'a pas apporté de résultats statistiquement significatifs. Cela indique l'absence d'une norme de la durée de l'allaitement maternel, spécifique pour la population du centre ou de l'arrière-pays. Cependant, la variabilité nettement supérieure dans la durée de l'allaitement maternel, observée dans le groupe de Mikulčice, doit être considérée comme une différence biologique significative. Les premiers enfants de Mikulčice ont été sevrés durant la deuxième année de vie, alors que d'autres enfants consommaient encore des quantités importantes de lait maternel à l'âge de 4-5 ans. Dans le groupe de Josefov, tous les enfants âgés de moins de deux ans étaient allaités. Durant la troisième année de vie, nous observons une forte baisse des valeurs isotopiques ($\Delta^{15}N_{t\text{-}b}$) et certains enfants étaient pleinement sevrés dans ce groupe d'âge. Compte tenu du faible nombre d'individus dans la catégorie des 3–5 ans, il est impossible de dire exactement quand le processus de sevrage a pris fin chez la population de l'arrière-pays. Les causes possibles de la variabilité supérieure de la durée de l'allaitement maternel chez la population du centre peuvent être les stratégies différentes de sevrage dans les différents groupes socio-économiques, la présence de migrants ou la pression des règles chrétiennes (Bartoňková et al. 1971). Il est toutefois important de souligner que dans le nombre relativement faible d'échantillons analysés, on a pu observer des tendances largement influencées par toute une série de facteurs individuels (par ex l'état de santé de la mère ou de l'enfant) insaisissables dans le contexte archéologique (Mulder-Sibanda et Sibanda-Mulder 1999 ; Simondon et al. 2001).

La comparaison des valeurs isotopiques du groupe des immatures avec le groupe de femmes (mères potentielles) indique que la stratégie intra-individuelle de l'échantillonnage a été choisie correctement. La forte variabilité des données isotopiques du groupe de femmes empêche l'utilisation d'une stratégie « transversale » où la diminution des valeurs isotopiques des enfants relativement au niveau de celles des adultes est considérée comme un signe de sevrage. La variabilité du groupe de femmes, notamment à Mikulčice, est tellement élevée qu'une grande proportion d'enfants allaités par des mères avec des valeurs isotopiques inférieures pourrait être considérée de façon erronée comme des enfants sevrés.

Néanmoins, la stratégie d'échantillonnage choisie a ses limites. Il s'agit tout d'abord du fait que pour un pourcentage important d'individus il est impossible de déterminer le type dominant d'alimentation, suite à la différence isotopique insuffisante ($\Delta^{15}N_{t\text{-}b}$). En outre, l'étude a concerné un groupe d'enfants qui n'a pas survécu à l'enfance et cela peut fausser considérablement la représentativité des données (Beaumont et al. 2015 ; Wood et al. 1992). En raison de l'impossibilité d'une détermination du sexe chez les immatures, il est également impossible de comparer la stratégie de sevrage entre les garçons et les filles, variable dans différentes populations (Eerkens et Bartelink 2013 ; Jayachandran et Kuziemko 2011). Cette partie de l'étude a été réalisée dans les années 2011-2012. Grâce au développement rapide de la spectrométrie de masse au cours des dernières années, la méthode de coupes en série de la dentine (Beaumont et al. 2013 ; 2015 ; Henderson et al. 2014) permettra d'étudier plus en détail dans le futur le processus de sevrage chez la population concernée.

10.5 La relation entre l'alimentation et les indicateurs de l'état de santé de la population de la Grande-Moravie

L'hypothèse de base testée dans cette partie du travail propose que l'alimentation monotone basée principalement sur les céréales avec une faible proportion de protéines animales conduit à la détérioration de la santé (Armelagos et Cohen 1984 ; Bennike 1985 ; Bocquet-Appel et al. 2008 ; Brinch et Moller-Christensen 1949 ; El-Najjar 1976 ; 1982 ; El-Najjar et al. 1975 ; 1976 ; Hillson 1996 ; Larsen 1997 ; Larsen et al. 1995 ; Lukacs 1992 ; Milner 1984 ; Moore et Corbett 1971 ; 1973 ; 1975 ; Powell 1985 ; Sledzik et Moore-Jansen 1991). Chez les individus consommant une faible proportion de protéines animales, des fréquences plus élevées de pathologies dentaires et d'indicateurs de stress non spécifiques sont attendues. Une autre hypothèse fondée sur le principe du paradoxe ostéologique (Wood et al. 1992) propose qu'une 'alimentation de qualité prolonge la durée de survie et fournit suffisamment de temps pour le développement des changements pathologiques.

Pour tous les signes ostéologiques, l'existence d'une relation significative entre ces indicateurs et les données démographiques (âge et sexe) a tout d'abord été vérifiée. Conformément aux résultats de cette analyse et du type de données, une méthode statistique appropriée a été choisie pour vérifier la relation entre les valeurs isotopiques et les signes ostéologiques.

Les résultats de l'évaluation statistique ont montré une relation significative entre les caractéristiques de l'alimentation et l'incidence des pathologies dentaires. Le groupe de femmes a enregistré une faible proportion de protéines animales dans l'alimentation associée à des fréquences plus élevées de caries et de maladie parondontale. Une tendance similaire mais moins nette a été observée au niveau des caries dans le groupe des hommes. Ces résultats sont conformes à l'hypothèse mentionnée ci-dessus. Toutefois, il est beaucoup plus difficile d'expliquer la relation significative entre l'intensité du taux de caries dentaires, le niveau d'abrasion dentaire et les valeurs des isotopes stables du carbone, observés dans le groupe des hommes. Leurs valeurs isotopiques indiquent que les hommes qui consomment des quantités plus élevées de millet avaient moins de caries et de dents moins usées. Hypothétiquement, l'explication peut être liée à la texture des aliments. Le millet a été probablement consommé sous forme de bouillie (Beranová 2005). Sa consommation accrue peut indiquer une préférence pour les fines purées, qui conduit à une abrasion dentaire inférieure et un nombre inférieur de caries (Hillson 2005 ; Larsen 1997). Cependant, cette tendance n'a pas été enregistrée chez les femmes.

Pour les indicateurs de stress non spécifiques, aucune influence significative de l'alimentation sur la stature et la présence de *cribra orbitalia* n’a été observée. L'explication peut être une étiologie multifactorielle où la qualité de l'alimentation est seulement un des facteurs potentiels de la formation de lésions (Walker et al. 2009 ; Wapler et al. 2004). Concernant la stature, elle peut refléter les conditions de vie pendant la période de croissance et de développement (Bogin 1999), alors que les isotopes stables reflètent l'alimentation au cours des dernières années de vie (Hedges et al. 2007).

Dans le cas des immatures, la comparaison des données isotopiques et ostéologiques au niveau individuel s'est avérée impossible en raison du faible nombre d'individus dont les valeurs isotopiques ont été obtenues. L'évaluation ostéologique de l'état de santé par rapport à l'alimentation consistait à vérifier l'hypothèse selon laquelle les différences de durée d'allaitement maternel entre les populations du centre et de l'arrière-pays (variabilité supérieure de la durée d'allaitement maternel chez la population du centre) se reflètent de manière adéquate dans les profils de morbidité des deux groupes de population. Selon l'hypothèse basée sur les résultats isotopiques, la présence des indicateurs de stress non spécifiques était répartie de manière uniforme dans les différentes catégories d'âge de la population du centre, alors que l'augmentation des maladies et de la mortalité au cours de la troisième année de vie a été observée chez la population de l'arrière-pays. Cependant, les résultats de la régression logistique n'ont pas montré l'existence de différences dans l'incidence des indicateurs de stress non spécifiques entre les groupes du centre et de l'arrière-pays, ni des différences dans la répartition des maladies par rapport à l'âge. L'étude de la croissance n'indique pas de différences significatives entre les deux groupes pour la plupart des dimensions, alors que les enfants de l'arrière-pays atteignaient dans tous les cas des dimensions légèrement inférieures.

Les études de ce type sont jusqu'à présent peu nombreuses mais les résultats actuels indiquent que le niveau de stress biologique était très variable au sein des populations archéologiques (Howcroft et al. 2012 ; Mays 2010 ; Pearson et al. 2010 ; Schurr 1997). La population de la Grande-Moravie fait partie des populations qui n'enregistrent pas une relation de cause à effet entre la durée de l'allaitement maternel et les maladies. Il semble que la majorité de la population ait bénéficié des avantages de l'allaitement maternel prolongé. Il convient toutefois de mentionner que la stratégie d'échantillonnage choisie permet de détecter uniquement la diminution significative de la consommation de lait maternel et non l'introduction des premiers compléments alimentaires qui pouvaient être un facteur plus important en matière de risque biologique d'infection (par ex. Newman 1995).

Ces résultats associés aux limités méthodologiques mentionnées (voir ci-dessus) ont pu contribuer au non enregistrement d'une relation potentiellement existante. Comme mentionné ci-dessus, l'étape suivante dans ce domaine devrait être l'utilisation de la méthode des coupes en série de la dentine, qui permet de suivre en détail le processus de sevrage.

10.6 Conclusions principales

Les résultats de l'analyse isotopique indiquent une stratification socio-économique avancée de la société de la Grande-Moravie, qui se manifeste par une contribution variable des protéines animales selon les différents groupes de la population. Les habitants des centres avaient en moyenne une comsommation plus importante des protéines animales que les habitants de l'arrière-pays. Dans le groupe des hommes de la population des centres, le statut socio-économique de l'individu (conformément à la richesse des tombes) avait également un impact significatif sur la consommation de ce composant alimentaire. Une tendance similaire n'a pas été observée chez les femmes. L'analyse isotopique des animaux (principalement les porcs) et des différents groupes humains indique que malgré le développement sans précédent des centres de la Grande-Moravie, leur degré d'urbanisation était relativement faible. En effet, le degré d'urbanisation n'apparaît en relation ni avec la détérioration de la qualité de l'alimentation des membres des groupes socio-économiques défavorisés, ni avec le changement des valeurs isotopiques des porcs, qui pourrait indiquer le passage de l'élevage extensif à l'élevage urbain.

Des changements significatifs ont été observés au niveau de l'alimentation entre les groupes de la Grande-Moravie et de la période late Hillfort, notamment avec la consommation marquée de millet et la baisse de la consommation des protéines animales pour les hommes. Ces résultats indiquent également que le comportement alimentaire des sujets masculins était plus sensible aux changements des conditions socio-économique ques celui des femmes dont le régime alimentaire était plus stable dans tous les groupes socio-économiques et entre les différentes périodes.

Bien que les facteurs alimentaires soient considérés par de nombreux auteurs comme la cause probable des changements observés de l'état sanitaire au niveau de la population (par ex. Larsen 1997), ce travail représente une des premières tentatives de regrouper les données isotopiques et les marqueurs ostéologiques de l'état de santé au niveau individuel. Alors que la relation prouvée entre le caractère de l'alimentation et l'état de la dentition doit être vérifiée dans un groupe plus nombreuse, ce résultat indique le haut potentiel de l'étude de l'alimentation, via les analyses isotopiques, pour comprendre les différences inter- et intra-démographiques, ainsi que certains aspects de l'état de santé.

Le groupe des immatures présente une forte variabilité de la durée de l'allaitement maternel, en particulier chez la population du centre de Mikulčice. Cela indique que probablement plusieurs pratiques étaient en vigueur au travers de la Grande-Moravie. L'évaluation ostéologique montre que les stratégies d'allaitement et de sevrage n'ont pas affecté de façon significative le risque de stress biologique auquel les populations du centre et de l'arrière-pays ont dû faire face.

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LIST OF ABBREVIATIONS

AP	antero-posterior diameter at the midshaft
GMC	Great Moravian centers
GMH	Great Moravian hinterland
ICE	caries intensity index
Jos	Josefov
LH	late Hillfort sample
Mik	Mikulčice
ML	medio-lateral diameter at the midshaft
N	Number of individuals
NP	not present
NS	no statistical analysis was performed
SD	standard deviation

LIST OF TABLES

TABLE 1. Acceptable ranges of collagen quality indicators in the stable isotope analysis of carbon and nitrogen 42
TABLE 2. Acceptable ranges for collagen quality indicators in the stable isotope analysis of sulphur 42
TABLE 3. Description of studied sample....53
TABLE 4. P-value of Spearman's rank correlation: dependence between isotopic values (δ^{15}N, δ^{13}C) and collagen preservation criteria in animal sample 71
TABLE 5. Basic statistics of animal sample 74
TABLE 6. Comparative data set of animal isotopic values....75
TABLE 7. Human bone collagen δ^{13}C and δ^{15}N (mean ± 1 standard deviation) and human-faunal offsets from medieval sites in Central Europe....87
TABLE 8. P-value of Spearman's rank correlation: dependence between isotopic values (δ^{15}N, δ^{13}C) and collagen preservation criteria in Mikulčice sample....88
TABLE 9. Basic statistics of the Mikulčice sample 90
TABLE 10. The impact of biological and socio-economic factors on human isotopic values in the Mikulčice sample, the results of t-test/Mann Whitney test 91
TABLE 11. Pairwise comparison of groups according to socio-economic status classified according to Unzeitigová (2000) 91
TABLE 12. P-value of Spearman's rank correlation: dependence between isotopic values (δ^{15}N, δ^{13}C) and collagen preservation criteria in Pohansko sample....93
TABLE 13. Basic statistics of the Pohansko sample....95
TABLE 14. The impact of biological and socio-economic factors on human isotopic values in the Pohansko sample, the results of t-test/Mann-Whitney test/linear regression 96
TABLE 15. Pairwise comparison of groups according to the socio-economic status in the sample of Pohansko classified according to Unzeitigová (2000) 97
TABLE 16. P-value of Spearman's rank correlation: dependence between isotopic values (δ^{15}N, δ^{13}C) and collagen preservation criteria in Josefov sample 100
TABLE 17. Basic statistics of the Josefov 1 sample 100
TABLE 18. The impact of biological and socio-economic factors on human isotopic values in the Josefov 1 sample, the results of Mann Whitney test....103
TABLE 19. Pairwise comparison of groups according to the socio-economic status in the sample of Josefov I classified according to Unzeitigová (2000) 103

TABLE 20. P- value of Spearman's rank correlation: dependence between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in the late Hillfort sample............................105
TABLE 21. The comparison of isotopic values between the late Hillfort population sample from Josefov II and Louky - the results of Mann-Whitney test...105
TABLE 22. Basic statistics of the late Hillfort sample..107
TABLE 23. The impact of biological and socio-economic factors at human isotopic values in the late Hillfort sample, the results of Mann-Whitney test...109
TABLE 24. Isotopic differences between defined groups of the Great Moravian and late Hillfort population: the results of t-test/ANOVA (including pairwise comparison between population samples), p-values..109
TABLE 25. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in sub-adult human sample from Mikulčice123
TABLE 26. P-value of Spearman's rank correlation: dependence between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in sub-adult human sample from Josefov 126
TABLE 27. Factors associated with the weaned status (vs. breastfed status): simple and multiple logistic regressions 129
TABLE 28. The relationship between isotopic data, skeletal health markers and demographic indicators...142
TABLE 29. Factors associated with the presence of cribra orbitalia: the results of the logistic regression (p-values)..143
TABLE 30. The relationship between the isotopic indicators of diet and the presence of caries: the results of the Mann-Whitney test 144
TABLE 31. The relationship between isotopic indicators of diet and ICE: the results of GLM analysis (p-values) 146
TABLE 32. The relationship between the isotopic indicators of diet and the periodontal disease/periapical lesions in the individuals older than 35 years: the results of the Mann-Whitney test 146
TABLE 33. Factors associated with the presence of periodontal disease: the results of logistic regression (p-values)..147
TABLE 34. The relationship between isotopic indicators of diet and dental wear: the results of GLM analysis (p-values)..149
TABLE 35. The relationship between the isotopic indicators of diet and the femur length: Kendall´s tau correlation (p-values) 150
TABLE 36. Age distribution and prevalence of stress indicators by age category 153

TABLE 37. Factors associated with the presence of non-specific stress indicators: the results of logistic regression (p-values) 155
TABLE 38. The effect of type of residency on the standardized residuals of the polynomial regression on biometric measures upon dental age 157

LIST OF FIGURES

Fig. 1. Extension of Great Moravia and neighbouring European empires in the latter third of the 9th century and the location of Mikulčice centre, modified illustration according to Poulík (1975), Havelková et al. (2010) and Kaupová et al. (2014). 20
Fig. 2. Location of studied sites, modified illustration according to Havelková et al. (2010) and Kaupová et al. (2014). 52
Fig. 3. Great Moravian settlement agglomeration of Mikulčice (modified according to Poláček 2008b). 54
Fig. 4. Pohansko - north-east suburb: rotunda with the adjacent cemetery (modified according to Macháček et al. 2014). Altitude of the bases of the graves is marked by colors. 57
Fig. 5. Josefov: Great Moravian burial site (Josefov I) at left, partially explored late Hillfort burial site (Josefov II) at right (modified according to Klíma 2007). 60
Fig. 6. Prušánky I burial site (modified according to Klanica 2006). 61
Fig. 7. Louky od Břeclavska burial site (modified according to Dresler 2013). Grave No. 9 was found isolated outside the main excavated area. 62
Fig. 8. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in animal sample. 72
Fig. 9. Animal and human (mean, percentile 2.5 and 97.5) isotopic data for all sites. Mik = Mikulčice; POH = Pohansko; GMH = Great Moravian hinterland; LH = late Hillfort sample; NP = not present. 73
Fig. 10. Animal data in comparison with other European medieval sites (median, percentile 2.5 and 97.5 when No. of samples higher than 5). A: domesticated animals; B: wild herbivores; C: fish. GMH = Great Moravian hinterland; LH = late Hillfort sample. 76
Fig. 11. Fish and human (mean, percentile 2.5 and 97.5) isotopic data for all sites; Mik = Mikulčice; POH = Pohansko; GMH = Great Moravian hinterland; LH = late Hillfort sample; NP = not present. 81
Fig. 12. Relationship between sulphur isotopic values and collagen preservation criteria in animal sample. Samples considered by Nehlich et al. 2010 as well preserved though outside the recommended range marked. 83
Fig. 13. Complete sulphur isotopic data. Potentially contaminated samples highlighted in red. 84
Fig. 14. Human and animal (median, percentile 2.5 and 97.5 with the exception of dogs and fowl) isotopic data for all sites. 86

Fig. 15. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in Mikulčice adult sample. 89
Fig. 16. The relationship between biological and socio-economic factors and human isotopic values in the Mikulčice sample. A = graves with weapons, gold, silver or bronze objects; B = graves with objects of daily use; C = without grave goods. 92
Fig. 17. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in Pohansko adult sample. 94
Fig. 18. The relationship between biological and socio-economic factors and human isotopic values in the Pohansko sample. A = graves with weapons, gold, silver or bronze objects; B = graves with objects of daily use; C = without grave goods; ND = undetermined sex. 98
Fig. 19. The relationship between socio-economic factors and human isotopic values in the Pohansko sample....................99
Fig. 20. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in Josefov adult sample. 101
Fig. 21. The relationship between biological and socio-economic factors and human isotopic values in the Josefov sample. A = graves with weapons, gold, silver or bronze objects, B = graves with objects of daily use, C = without grave goods. 104
Fig. 22. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in late Hillfort sample. 106
Fig. 23. The relationship between biological and socio-economic factors and human isotopic values in the late Hillfort sample. ND = undetermined sex. 108
Fig. 24. Comparison of human bone collagen isotopic values between the Great Moravian centers of Mikulčice and Pohansko. ND = undetermined sex. 111
Fig. 25. The relation between nitrogen isotopic data (median, 1st quartile, 3rd quartile, min, max) and indicators of socio-economic status in the Great Moravian centers. A: $\delta^{15}N$ vs. the quality of grave goods in the sample of Mikulčice (A = graves with weapons, gold, silver or bronze objects; B = graves with objects of daily use; C = without grave goods). B: $\delta^{15}N$ vs. the presence of grave construction in the sample of Pohansko. 112
Fig. 26. Comparison of human bone collagen isotopic values between the Great Moravian centers (GMC) and hinterland (GMH). ND = undetermined sex. 114
Fig. 27. Comparison of human bone collagen isotopic values between the Great Moravian hinterland (GMH) and late Hillfort (LH) samples. ND = undetermined sex. 117

Fig. 28. Complete bone apatite isotopic values in relation to the bone collagen isotopic values. A: $\delta^{13}C_{ap}$ *vs.* $\delta^{13}C_{coll}$; B: $\delta^{13}C_{ap}$ *vs.* $\delta^{15}N$; C: $\Delta^{13}C_{(ap\text{-}coll)}$ *vs.* $\delta^{15}N$. 119
Fig. 29. The position of Great Moravian and late Hillfort individuals in the plot according to Kellner and Schoeninger (2007). 120
Fig. 30. $\delta^{13}C_{ap}$ and $\delta^{13}C_{coll}$ of Great Moravian and late Hillfort samples in comparison with: A: original data by Kellner and Schoeninger (2007) for population groups consuming C_3 protein and C_3 energy sources / C_3 protein and C_4 energy sources; B: other Central European medieval sites. 122
Fig. 31. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in tooth and bone samples of Mikulčice sub-adult sample..124
Fig. 32. Suggested feeding status of Mikulčice children based on relative differences between the tooth dentin and bone samples ($\Delta^{15}N_{t\text{-}b}$). 125
Fig. 33. Relationship between isotopic values ($\delta^{15}N$, $\delta^{13}C$) and collagen preservation criteria in tooth and bone samples of Josefov sub-adult sample..127
Fig. 34. Suggested feeding status of Josefov children based on relative differences between the tooth dentin and bone samples ($\Delta^{15}N_{t\text{-}b}$). 128
Fig. 35. $\Delta^{13}C_{t\text{-}b}$ in relation to $\Delta^{15}N_{t\text{-}b}$ in the Josefov and Mikulčice sample. 134
Fig. 36. The $\delta^{15}N$ and $\delta^{13}C$ values of sub-adult individuals plotted against the age at death and according to whether the sample was derived from bone or dentine. The three horizontal lines represent the adult female mean (solid line) and two standard deviations above and below this mean (dashed lines). Individual JOSS20 (discussed in the text) is labelled. 139
Fig. 37. The relationship between the presence *vs.* absence of *cribra orbitalia* and human isotopic values. 143
Fig. 38. The relationship between the presence *vs.* absence of at least one caries lesion or *ante-mortem* tooth loss and human isotopic values. 144
Fig. 39. The relationship between the caries intensity (ICE) and human isotopic values. 145
Fig. 40. The relationship between the presence *vs.* absence of the periodontal disease and human isotopic values. In case of males, the low number of individuals under 35 years with present periodontal disease prevented the classification according to age-at-death.......147
Fig. 41. The relationship between the presence *vs.* absence of the periapical lesions and human isotopic values. 148
Fig. 42. The relationship between the dental wear score and human isotopic values. 149

Fig. 43. The relationship between the femur lenght as an approximation of stature and human isotopic values. 150

Fig. 44. True prevalence rate (TPR; % individuals with bone element present) of stress indicators in the Mikulčice and Josefov sample by age category. 154

Fig. 45. Lineal regressions or second order polynomials for bone dimensions on dental age according to the urban versus rural place of residence and suggested feeding status. AP, ML = antero-posterior, medio-lateral diameter at the midshaft; Age = median dental age in years. 156

Fig. 46. $\Delta^{15}N_{t\text{-}b}$ according to the presence of non-specific stress indicators (for both Mikulčice and Josefov samples). 159

LIST OF EQUATIONS

Equation 1 28
Equation 2 66
Equation 3 68

APPENDIX: DATASETS (COMPLETE ISOTOPIC DATA)

TABLE A1. Complete animal isotopic data

Sample Code	Site	Species	Species (lat.)	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{V\text{-}PDB}$ (‰)
MIKF01	Mikulčice	Cattle	*Bos taurus*	2.1	12.0	33.8	3.3	7.2	-20.5
MIKF02	Mikulčice	Cattle	*Bos taurus*	1.6	11.3	31.7	3.3	6.2	-20.4
MIKF03	Mikulčice	Horse	*Equuscaballus*	4.5	13.9	37.8	3.2	5.5	-21.9
MIKF04	Mikulčice	Sheep/goat	*Ovis/Capra*	19.7	15.3	42.1	3.2	7.4	-20.4
MIKF05	Mikulčice	Sheep/goat	*Ovis/Capra*	14.7	16.5	45.0	3.2	8.4	-20.4
MIKF06	Mikulčice	Pig	*Susscrofadomestica*	13.6	14.8	40.8	3.2	7.3	-20.7
MIKF07	Mikulčice	Fowl	*Gallusdomesticus*	12.5	14.9	41.2	3.2	9.6	-18.4
MIKF08	Mikulčice	Fowl	*Gallusdomesticus*	1.3	13.3	38.1	3.3	10.6	-16.7
MIKF09	Mikulčice	Roe-deer	*Capreoluscapreolus*	12.4	12.7	35.6	3.3	7.4	-21.3
MIKF10	Mikulčice	Sheep/goat	*Ovis/Capra*	6.5	12.0	32.9	3.2	4.7	-20.9
MIKF11	Mikulčice	Red-deer	*Cervuselaphus*	5.2	14.7	40.5	3.2	4.8	-20.4
MIKF12	Mikulčice	Wild boar	*Susscrofa*	2.3	12.8	36.9	3.4	9.4	-20.3
MIKF13	Mikulčice	Dog	*Canisfamiliaris*	18.7	13.6	37.3	3.2	10.0	-19.0
MIKF14	Mikulčice	Red-deer	*Cervuselaphus*	8.8	14.0	38.8	3.2	4.4	-20.9
MIKF15	Mikulčice	Cattle	*Bos taurus*	2.1	12.3	34.1	3.2	4.8	-20.4
MIKF17	Mikulčice	Bear	*Ursusarctos*	15.3	14.5	40.0	3.2	6.3	-19.4
MIKF18	Mikulčice	Bear	*Ursusarctos*	12.6	14.5	40.6	3.2	5.9	-19.6
MIKF19	Mikulčice	Beaver	*Castor fiber*	13.3	16.2	44.2	3.2	6.0	-21.8
MIKF20	Mikulčice	Pig	*Susscrofadomestica*	6.4	11.8	33.1	3.2	7.1	-20.7
MIKF21	Mikulčice	Fowl	*Gallusdomesticus*	14.4	15.6	43.0	3.2	10.7	-17.9
MIKF22	Mikulčice	Pig	*Susscrofadomestica*	13.9	15.3	41.7	3.2	7.5	-20.7
MIKF23	Mikulčice	Sheep/goat	*Ovis/Capra*	14.3	15.4	41.6	3.1	8.6	-20.5

Sample Code	Site	Species	Species (lat.)	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{V\text{-}PDB}$ (‰)
MIKF24	Mikulčice	Sheep/goat	*Ovis/Capra*	14.4	15.1	41.7	3.2	7.1	-21.0
MIKF25	Mikulčice	Pig	*Susscrofadomestica*	13.7	15.2	41.6	3.2	5.7	-20.3
MIKF26	Mikulčice	Pig	*Susscrofadomestica*	4.4	12.5	34.8	3.2	10.5	-19.6
MIKF27	Mikulčice	Red-deer	*Cervuselaphus*	5.7	13.9	37.9	3.2	4.7	-20.9
MIKF28	Mikulčice	Sheep/goat	*Ovis/Capra*	15.6	15.3	42.1	3.2	5.9	-20.2
MIKF29	Mikulčice	Horse	*Equuscaballus*	13.2	15.3	41.8	3.2	7.0	-22.0
MIKF30	Mikulčice	Dog	*Canisfamiliaris*	3.9	13.5	37.7	3.3	9.1	-19.0
MIKF31	Mikulčice	Dog	*Canisfamiliaris*	19.2	16.1	44.2	3.2	9.3	-17.3
MIKF32	Mikulčice	Cattle	*Bos taurus*	2.0	11.4	33.5	3.4	6.5	-20.2
MIKF33	Mikulčice	Cattle	*Bos taurus*	17.1	13.7	38.3	3.2	7.2	-20.5
MIKF35	Mikulčice	Fish(ND)[a]	*Teleostei*	12.9	13.8	38.1	3.2	6.9	-25.4
MIKF38	Mikulčice	Fish (ND)[a]	*Teleostei*	12.2	14.1	39.1	3.2	8.9	-25.6
MIKF39	Mikulčice	Carp	*Cyprinuscarpio*	12.6	14.0	38.9	3.2	7.8	-24.3
MIKF40	Mikulčice	Pike	*Esoxlucius*	7.6	13.6	39.3	3.4	11.5	-22.9
MIKF41	Mikulčice	Fish (ND)[a]	*Teleostei*	11.6	15.7	43.0	3.2	7.2	-25.4
MIKF42	Mikulčice	Dace	*Leuciscussp.*	15.6	12.8	34.5	3.1	12.9	-21.8
POHF01	Pohansko	Fish (ND)[a]	*Teleostei*	8.7	13.3	38.2	3.3	8.7	-26.2
POHF02	Pohansko	RedDeer	*Cerphuselaphus*	3.4	14.4	40.2	3.2	5.3	-21.1
POHF03	Pohansko	Fowl	*Gallusdomesticus*	4.6	16.5	45.0	3.2	9.9	-18.0
POHF04	Pohansko	Sheep/goat	*Ovis/Capra*	18.2	16.5	45.2	3.2	7.2	-20.8
POHF05	Pohansko	Dog	*Canisfamiliaris*	2.3	14.7	40.9	3.2	9.2	-17.0
POHF06	Pohansko	Cattle	*Bos taurus*	10.5	12.8	35.4	3.2	6.5	-19.4
POHF07	Pohansko	Pig	*Susscrofadomestica*	10.2	15.0	41.1	3.2	6.3	-21.4
POHF08	Pohansko	Beaver	*Castor fiber*	3.2	14.8	41.5	3.3	7.6	-22.0

Sample Code	Site	Species	Species (lat.)	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{V\text{-}PDB}$ (‰)
POHF09	Pohansko	Wildboar	*Susscrofa*	2.9	14.8	40.8	3.3	6.6	-20.5
JOSF02	Josefov	Pig (subadult)	*Susscrofadomestica*	4.3	15.1	43.3	3.3	7.8	-19.7
JOSF03	Josefov	Fowl	*Gallusdomesticus*	4.1	14.3	41.2	3.3	7.7	-16.2
JOSF04	Josefov	Fowl	*Gallusdomesticus*	4.0	14.1	40.4	3.3	8.2	-17.9
MUTF01	Mutěnice	Cattle	*Bos taurus*	2.6	14.4	40.5	3.3	8.1	-18.8
MUTF02	Mutěnice	Sheep/goat	*Ovis/Capra*	16.4	16.4	45.0	3.2	5.9	-21.0
MUTF03	Mutěnice	Pig	*Susscrofadomestica*	11.1	16.6	45.9	3.2	6.4	-20.3
MUTF04	Mutěnice	Cattle	*Bos taurus*	4.3	15.3	42.7	3.2	6.3	-20.1
MUTF05	Mutěnice	Horse	*Equuscaballus*	6.9	14.9	41.1	3.2	5.6	-22.2
MUTF06	Mutěnice	Sheep/goat	*Ovis/Capra*	3.8	14.7	41.3	3.3	6.7	-21.6
MUTF07	Mutěnice	Sheep/goat	*Ovis/Capra*	8.0	15.6	43.0	3.2	8.1	-19.5
MUTF08	Mutěnice	Pig	*Susscrofadomestica*	16.2	15.6	42.4	3.2	7.2	-20.5
MUTF09	Mutěnice	Fowl	*Gallusdomesticus*	7.4	14.8	41.4	3.2	8.1	-15.6
MUTF10	Mutěnice	Cattle	*Bos taurus*	11.8	16.1	44.2	3.2	7.8	-17.1
MUTF11	Mutěnice	Pig	*Susscrofadomestica*	10.2	15.0	42.0	3.3	6.9	-20.2
MUTF12	Mutěnice	Sheep/goat	*Ovis/Capra*	7.8	16.4	45.2	3.2	9.4	-20.6
MUTF13	Mutěnice	Horse	*Equuscaballus*	6.6	15.0	42.1	3.3	8.3	-21.2
MUTF14	Mutěnice	Pig	*Susscrofadomestica*	3.3	14.0	39.3	3.3	8.8	-20.2
MUTF15	Mutěnice	Cattle	*Bos taurus*	4.0	14.6	40.5	3.2	7.6	-19.9
KOSF01	Kostice	Cattle	*Bos taurus*	3.3	14.3	39.3	3.2	6.5	-20.9
KOSF02	Kostice	Cattle	*Bos taurus*	16.0	16.5	45.1	3.2	5.1	-21.2
KOSF03	Kostice	Cattle	*Bos taurus*	10.8	15.7	43.1	3.2	6.0	-20.0
KOSF04	Kostice	Sheep/goat	*Ovis/Capra*	8.9	16.4	45.0	3.2	7.2	-21.9
KOSF05	Kostice	Sheep/goat	*Ovis/Capra*	7.8	16.1	44.2	3.2	6.0	-21.6

Sample Code	Site	Species	Species (lat.)	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{V\text{-}PDB}$ (‰)
KOSF06	Kostice	Sheep/goat	*Ovis/Capra*	12.5	16.7	45.7	3.2	6.6	-20.3
KOSF07	Kostice	Pig	*Susscrofadomestica*	4.4	14.3	39.5	3.2	3.3	-19.3
KOSF08	Kostice	Pig	*Susscrofadomestica*	8.5	15.8	43.9	3.2	3.1	-20.8
KOSF09	Kostice	Pig	*Susscrofadomestica*	12.1	16.2	44.3	3.2	7.1	-20.0
KOSF10	Kostice	Fowl	*Gallusdomesticus*	11.1	15.4	42.7	3.2	10.0	-12.0

[a]ND – undetermined species.

TABLE A2. Complete animal sulphur isotopic data[a]

Sample Code	Site	Species	Species (lat.ú	Carbon Content	Nitrogen Content	Sulfur Content	C/N	C/S	N/S	$d^{34}S_{V\text{-}CDT}$
MikF04	Mikulčice	Sheep/goat	*Ovis aries*	42.1	15.3	0.2	3.2	546.1	170.4	-0.9
MIKF06	Mikulčice	Pig	*Sus domesticus*	40.8	14.8	0.2	3.2	527.9	164.4	2.1
MikF07	Mikulčice	Fowl	*Gallus domesticus*	41.2	14.9	0.2	3.2	464.3	143.7	3.8
MikF19	Mikulčice	Beaver	*Castor fiber*	44.2	16.2	0.2	3.2	499.0	156.3	-3.7
MikF21	Mikulčice	Fowl	*Gallus domesticus*	43.0	15.6	0.2	3.2	493.4	153.6	1.1
MikF22	Mikulčice	Pig	*Sus domesticus*	41.7	15.2	0.2	3.2	558.8	175.1	1.0
MikF23	Mikulčice	Sheep/goat	*Ovis aries*	41.6	15.4	0.2	3.1	562.4	178.4	4.4
MikF24	Mikulčice	Sheep/goat	*Ovis aries*	41.7	15.1	0.2	3.2	550.2	171.1	6.9
MikF25	Mikulčice	Pig	*Sus domesticus*	41.6	15.1	0.2	3.2	538.4	167.9	3.3
MikF28	Mikulčice	Sheep/goat	*Ovůis aries*	42.1	15.3	0.2	3.2	555.6	172.8	-3.4
MikF29	Mikulčice	Horse	*Equus caballus*	41.8	15.3	0.2	3.2	579.3	181.6	1.9
MikF33	Mikulčice	Cattle	*Bos taurus*	38.3	13.7	0.2	3.2	470.9	144.5	-4.2
MikF35	Mikulčice	Fish (ND)	*Teleostei*	38.1	13.8	0.4	3.2	**235.3**	73.3	12.3
MikF38	Mikulčice	Fish (ND)	*Teleostei*	39.1	14.1	0.4	3.2	**239.7**	74.1	5.0
MikF39	Mikulčice	Carp	*Cyprinus carpio*	38.9	14.0	0.4	3.2	**235.3**	72.6	3.1
MikF40	Mikulčice	Pike	*Esox lucius*	39.3	13.6	0.5	3.4	207.9	61.6	-7.2
MikF41	Mikulčice	Fish (ND)	*Teleostei*	43.0	15.7	0.4	3.2	**266.5**	**83.4**	7.1
MikF42	Mikulčice	Dace	*Leuciscus sp.*	34.5	12.8	0.4	3.1	224.6	71.3	-7.9
POHF01	Pohansko	Fish (ND)	*Teleostei*	38.2	13.3	0.6	3.3	184.1	55.1	-10.3
POHF03	Pohansko	Fowl	*Gallus domesticus*	45.0	16.5	0.2	3.2	487.6	153.0	-2.1
POHF04	Pohansko	Sheep/goat	*Ovis aries*	45.2	16.5	0.2	3.2	561.1	175.9	0.3
POHF07	Pohansko	Pig	*Sus scrofa domestica*	41.1	15.0	0.2	3.2	510.5	159.8	0.4

[a]samples with carbon and nitrogen content higher than recommended maximum in bold font; ND – undetermined species.

TABLE A3. Complete human isotopic data (adults)[a]

Sample Code	Site	Grave No.	Sex	Age	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{PDB}$ (‰)
MIKH01	Mikulčice	39	Male	35+	18.1	13.4	37.0	3.2	11.3	-16.8
MIKH02	Mikulčice	44	Male	<35	20.3	15.1	41.4	3.2	11.3	-17.9
MIKH03	Mikulčice	49	Male	35+	20.9	15.9	43.4	3.2	10.6	-17.8
MIKH04	Mikulčice	51	Female	35+	18.9	15.1	41.7	3.2	11.6	-17.9
MIKH05	Mikulčice	56	Female	35+	21.4	15.8	43.6	3.2	10.7	-17.4
MIKH06	Mikulčice	61	Male	<35	20.3	14.9	41.1	3.2	10.2	-18.7
MIKH07	Mikulčice	62	Female	<35	4.3	14.0	38.3	3.2	10.3	-18.2
MIKH08	Mikulčice	94	Male	35+	18.1	14.8	40.9	3.2	10.1	-18.9
MIKH09	Mikulčice	96	Male	35+	18.6	15.7	43.0	3.2	10.8	-18.1
MIKH10	Mikulčice	122	Male	35+	19.8	15.6	43.1	3.2	10.1	-18.6
MIKH11	Mikulčice	130	Female	35+	20.2	15.7	43.4	3.2	10.7	-17.8
MIKH12	Mikulčice	131	Female	35+	20.7	16.9	46.5	3.2	10.7	-17.4
MIKH13	Mikulčice	142	Male	35+	20.0	16.1	44.5	3.2	11.4	-18.3
MIKH14	Mikulčice	154	Female	35+	19.4	15.4	42.4	3.2	11.1	-17.5
MIKH15	Mikulčice	165	Male	35+	3.6	13.3	37.3	3.2	11.1	-18.3
MIKH16	Mikulčice	167	Female	35+	20.0	15.5	42.5	3.2	10.0	-16.9
MIKH17	Mikulčice	186	Male	35+	17.3	14.7	40.5	3.2	11.3	-18.0
MIKH18	Mikulčice	198	Male	35+	19.9	16.0	44.0	3.2	9.8	-18.3
MIKH19	Mikulčice	199	Male	35+	16.9	15.2	41.8	3.2	10.0	-18.8
MIKH20	Mikulčice	223	Male	35+	19.3	16.2	43.9	3.1	12.6	-18.8
MIKH21	Mikulčice	228	Male	35+	20.4	16.2	44.1	3.2	12.0	-17.8
MIKH22	Mikulčice	232	Male	35+	20.2	15.6	42.0	3.1	11.1	-18.2

Sample Code	Site	Grave No.	Sex	Age	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{PDB}$ (‰)
MIKH23	Mikulčice	390	Male	<35	20.7	16.4	44.0	3.1	11.2	-17.5
MIKH24	Mikulčice	419	Female	<35	6.3	13.1	36.4	3.2	9.5	-18.7
MIKH25	Mikulčice	456	Female	35+	20.2	15.3	41.9	3.2	9.8	-18.6
MIKH26	Mikulčice	475	Female	35+	15.9	14.9	41.1	3.2	10.9	-17.5
MIKH27	Mikulčice	21	Female	35+	3.6	13.8	37.5	3.2	10.0	-18.5
MIKH28	Mikulčice	559	Male	35+	5.7	13.6	37.4	3.2	11.2	-17.8
MIKH29	Mikulčice	604	Male	35+	13.6	15.8	43.3	3.2	10.5	-18.4
MIKH30	Mikulčice	606	Male	<35	20.1	15.1	41.1	3.2	11.1	-17.8
MIKH31	Mikulčice	659	Female	35+	18.3	14.6	39.8	3.2	10.0	-17.7
MIKH32	Mikulčice	678	Female	35+	6.3	14.3	40.0	3.2	11.7	-17.7
MIKH33	Mikulčice	711	Female	35+	18.0	14.4	39.8	3.2	11.0	-17.9
MIKH34	Mikulčice	719	Female	<35	4.7	14.5	39.8	3.2	9.7	-18.1
MIKH35	Mikulčice	721	Male	<35	19.0	15.0	41.4	3.2	10.3	-17.1
MIKH36	Mikulčice	738	Female	35+	20.5	15.1	41.5	3.2	11.0	-17.6
MIKH37	Mikulčice	1197	Female	<35	20.8	16.6	45.5	3.2	8.7	-17.2
MIKH38	Mikulčice	1214	Female	35+	19.2	15.7	43.3	3.2	9.5	-17.7
MIKH39	Mikulčice	1216	Female	35+	15.9	14.5	39.5	3.2	9.0	-18.0
MIKH40	Mikulčice	1218	Female	35+	5.7	12.3	34.1	3.2	9.7	-18.1
MIKH41	Mikulčice	90	Male	35+	7.6	14.3	39.3	3.2	11.2	-17.1
MIKH42	Mikulčice	149	Female	35+	4.3	14.5	41.0	3.3	10.2	-18.2
MIKH43	Mikulčice	205	Female	35+	19.6	15.0	41.8	3.2	12.8	-18.7
MIKH44	Mikulčice	216	Female	<35	20.5	14.1	39.3	3.2	13.1	-18.6
MIKH45	Mikulčice	262	Female	35+	20.9	15.4	42.8	3.2	10.2	-18.2
MIKH46	Mikulčice	265	Male	35+	19.9	15.5	42.9	3.2	11.5	-18.6

Sample Code	Site	Grave No.	Sex	Age	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{PDB}$ (‰)
MIKH47	Mikulčice	269	Male	35+	19.9	15.7	42.9	3.2	11.5	-17.9
MIKH48	Mikulčice	272	Male	35+	18.0	14.8	41.3	3.2	12.7	-17.7
MIKH49	Mikulčice	353	Male	35+	20.2	13.8	38.4	3.2	11.0	-17.1
MIKH50	Mikulčice	433	Male	<35	21.6	15.4	42.5	3.2	10.5	-17.9
MIKH51	Mikulčice	501	Male	<35	19.3	15.3	43.0	3.3	11.7	-17.9
MIKH52	Mikulčice	505	Female	<35	19.8	15.1	42.2	3.2	11.6	-18.3
MIKH53	Mikulčice	625	Female	<35	20.1	13.9	38.8	3.2	10.3	-18.1
MIKH54	Mikulčice	627	Male	<35	19.1	13.3	37.5	3.3	11.3	-18.3
MIKH55	Mikulčice	645	Male	<35	20.2	14.3	40.1	3.3	10.7	-17.6
MIKH56	Mikulčice	649	Female	<35	15.8	14.0	38.8	3.2	11.5	-17.4
MIKH57	Mikulčice	464	Male	35+	22.5	13.3	37.1	3.2	11.3	-16.3
MIKH58	Mikulčice	398	Male	<35	20.1	14.1	39.1	3.2	12.1	-18.3
MIKH59	Mikulčice	689	Female	<35	17.7	14.8	40.8	3.2	10.4	-18.5
MIKH60	Mikulčice	701	Male	<35	5.8	13.1	38.2	3.4	10.6	-18.6
MIKH61	Mikulčice	736	Male	<35	6.5	14.5	41.2	3.3	10.3	-17.5
MIKH62	Mikulčice	1196	Female	<35	21.3	14.9	41.5	3.2	10.4	-18.3
MIKH63	Mikulčice	1217	Male	35+	21.2	15.8	43.9	3.2	10.2	-19.2
MIKH64	Mikulčice	275	Female	<35	19.6	14.9	41.3	3.2	12.2	-17.1
MIKH65	Mikulčice	389	Female	35+	18.0	13.9	38.8	3.2	11.6	-16.9
MIKH66	Mikulčice	602	Female	<35	20.6	13.6	37.6	3.2	10.5	-17.9
MIKH67	Mikulčice	742	Female	35+	16.0	13.2	36.5	3.2	11.6	-18.2
MIKH68	Mikulčice	366	Female	35+	18.2	14.8	40.8	3.2	10.7	-17.3
MIKH69	Mikulčice	412	Female	35+	21.2	13.7	37.7	3.2	12.3	-17.6
MIKH70	Mikulčice	520	Female	35+	17.6	15.5	43.1	3.2	11.2	-17.7

Sample Code	Site	Grave No.	Sex	Age	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{PDB}$ (‰)
POHH01	Pohansko	54	Male	35+	18.4	15.7	43.1	3.2	8.8	-15.6
POHH02	Pohansko	60	Male	35+	15.8	16.3	45.1	3.2	10.3	-18.4
POHH03	Pohansko	61	Male	<35	8.5	15.8	43.9	3.2	9.4	-17.9
POHH04	Pohansko	63	Male	35+	20.5	17.1	46.8	3.2	11.3	-18.3
POHH05	Pohansko	66	Male	35+	4.3	14.0	38.8	3.2	10.3	-17.5
POHH06	Pohansko	74	Male	<35	7.4	14.4	39.6	3.2	12.2	-18.4
POHH07	Pohansko	78	Female	35+	20.2	15.2	41.7	3.2	11.6	-18.4
POHH08	Pohansko	79	Male	35+	5.8	15.7	42.7	3.2	11.1	-17.6
POHH09	Pohansko	80	Male	35+	17.8	15.6	43.1	3.2	10.1	-17.6
POHH10	Pohansko	82	Female	35+	15.1	14.5	39.9	3.2	10.7	-18.4
POHH11	Pohansko	84	Female	35+	9.9	15.0	41.5	3.2	10.4	-19.5
POHH12	Pohansko	87	Male	<35	18.0	14.9	40.9	3.2	9.8	-17.8
POHH13	Pohansko	88	Male	35+	19.8	14.9	41.0	3.2	10.7	-17.1
POHH14	Pohansko	99	Female	35+	20.3	14.5	39.9	3.2	10.1	-17.2
POHH15	Pohansko	108	Female	35+	4.9	12.3	33.8	3.2	10.1	-18.4
POHH16	Pohansko	109	Female	<35	6.2	13.6	38.2	3.3	11.4	-18.5
POHH17	Pohansko	110	Male	<35	16.5	14.0	38.5	3.2	12.2	-17.8
POHH18	Pohansko	111	Female	35+	17.3	14.6	40.5	3.2	10.8	-18.0
POHH19	Pohansko	112	Male	35+	17.1	15.6	42.8	3.2	11.4	-18.2
POHH20	Pohansko	117	Female	<35	17.6	13.7	38.1	3.2	12.8	-17.9
POHH21	Pohansko	128	Female	35+	14.2	16.0	44.1	3.2	11.9	-18.5
POHH22	Pohansko	131	Female	<35	5.5	14.5	39.9	3.2	9.8	-17.9
POHH23	Pohansko	133	Male	35+	21.3	16.0	43.9	3.2	11.5	-18.2
POHH24	Pohansko	134	Female	35+	9.0	14.9	40.8	3.2	10.6	-18.1

Sample Code	**Site**	**Grave No.**	**Sex**	**Age**	**Yield (%)**	**Nitrogen Content (%)**	**Carbon Content (%)**	**C:N**	**$\delta^{15}N_{AIR}$ (‰)**	**$\delta^{13}C_{PDB}$ (‰)**
POHH25	Pohansko	138	Female	35+	18.7	16.1	44.3	3.2	8.2	-18.5
POHH26	Pohansko	143	Female	35+	8.1	15.5	42.7	3.2	11.7	-17.6
POHH27	Pohansko	145	Female	35+	18.0	15.9	43.6	3.2	10.6	-18.2
POHH28	Pohansko	151	Male	35+	16.4	15.9	43.5	3.2	10.1	-17.8
POHH29	Pohansko	153	Male	35+	16.2	14.9	41.2	3.2	12.5	-18.7
POHH30	Pohansko	154	Female	<35	20.3	11.1	31.0	3.2	11.2	-17.0
POHH31	Pohansko	155	Male	<35	17.3	16.8	46.1	3.2	8.4	-18.0
POHH32	Pohansko	157	Male	35+	15.6	17.3	47.7	3.2	13.1	-17.8
POHH33	Pohansko	158	Female	35+	15.8	16.6	45.8	3.2	10.2	-17.2
POHH34	Pohansko	162	Male	<35	19.2	**17.7**	**49.1**	3.2	10.7	-18.7
POHH35	Pohansko	165	Male	35+	6.0	15.1	41.6	3.2	10.4	-18.5
POHH36	Pohansko	166	Male	<35	17.4	14.6	40.5	3.2	12.0	-19.0
POHH37	Pohansko	168	Male	<35	8.1	16.4	45.0	3.2	9.7	-17.3
POHH38	Pohansko	169	Male	<35	18.5	16.3	44.7	3.2	9.6	-18.4
POHH39	Pohansko	173	Male	<35	19.4	16.4	44.8	3.2	9.7	-18.2
POHH40	Pohansko	174	Male	35+	19.2	14.8	40.6	3.2	9.9	-18.4
POHH41	Pohansko	179	Male	<35	18.3	15.4	42.5	3.2	9.7	-16.2
POHH42	Pohansko	184	Male	<35	21.6	15.3	42.9	3.3	10.6	-17.9
POHH43	Pohansko	185	Male	35+	20.5	14.6	40.1	3.2	10.9	-17.6
POHH44	Pohansko	187	Male	35+	12.2	15.8	43.1	3.2	11.6	-18.1
POHH45	Pohansko	189	Female	<35	18.2	14.6	40.6	3.2	9.3	-18.1
POHH46	Pohansko	190	Male	35+	20.9	14.8	41.0	3.2	10.7	-17.5
POHH47	Pohansko	191	Male	35+	17.3	15.2	42.0	3.2	11.9	-18.2
POHH48	Pohansko	193	Female	<35	6.3	15.5	42.9	3.2	11.2	-18.7

Sample Code	Site	Grave No.	Sex	Age	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{PDB}$ (‰)
POHH49	Pohansko	195	Female	35+	19.1	15.5	42.5	3.2	12.9	-18.4
POHH50	Pohansko	196	Female	35+	9.9	16.5	44.8	3.2	9.9	-17.9
POHH51	Pohansko	72	Male	35+	11.3	15.6	42.6	3.2	12.5	-18.2
POHH52	Pohansko	92	Female	35+	18.2	16.0	43.9	3.2	10.5	-18.1
POHH53	Pohansko	97	Female	35+	12.5	14.7	40.2	3.2	10.4	-18.3
POHH54	Pohansko	130	Female	35+	1.8	11.9	32.7	3.2	11.2	-18.3
POHH55	Pohansko	132	ND	<35	20.3	16.0	43.5	3.2	9.9	-17.7
POHH56	Pohansko	192	Female	35+	18.6	15.9	43.6	3.2	11.2	-17.9
JOSH01	Josefov	8	Female	<35	20.3	15.0	41.9	3.2	8.2	-17.5
JOSH02	Josefov	14	Male	35+	21.3	15.3	42.5	3.2	10.4	-18.3
JOSH03	Josefov	38	Male	<35	21.7	14.3	39.9	3.2	10.4	-18.5
JOSH04	Josefov	43	Female	35+	12.2	13.6	37.9	3.2	9.0	-16.8
JOSH05	Josefov	44	Female	35+	19.1	14.8	41.5	3.3	9.4	-17.3
JOSH06	Josefov	45	Male	35+	21.0	15.9	44.0	3.2	10.5	-17.9
JOSH07	Josefov	60	Female	35+	20.7	15.0	42.0	3.3	9.6	-17.5
JOSH08	Josefov	73	Female	35+	14.7	14.5	40.5	3.3	10.2	-17.1
JOSH09	Josefov	76	Female	35+	21.2	14.3	40.2	3.3	9.9	-18.6
JOSH10	Josefov	78	Male	35+	7.8	14.0	39.4	3.3	7.9	-18.1
JOSH11	Josefov	79	Female	35+	21.6	15.4	42.5	3.2	8.8	-18.8
JOSH12	Josefov	80	Female	35+	18.5	15.3	42.2	3.2	10.3	-17.3
JOSH13	Josefov	85	Male	35+	17.0	15.2	42.0	3.2	11.3	-19.8
JOSH14	Josefov	109	Male	35+	5.8	13.3	38.4	3.4	9.9	-19.0
JOSH15	Josefov	133	Male	35+	18.6	15.4	42.4	3.2	10.2	-18.2
JOSH16	Josefov	136	Male	<35	20.7	16.2	44.4	3.2	10.2	-17.5

Sample Code	**Site**	**Grave No.**	**Sex**	**Age**	**Yield (%)**	**Nitrogen Content (%)**	**Carbon Content (%)**	**C:N**	**$\delta^{15}N_{AIR}$ (‰)**	**$\delta^{13}C_{PDB}$ (‰)**
JOSH17	Josefov	137	Male	35+	20.8	14.2	39.6	3.2	9.6	-18.1
JOSH18	Josefov	170	Male	35+	20.8	15.9	44.1	3.2	10.2	-17.8
JOSH19	Josefov	90	Female	35+	19.4	15.6	43.4	3.2	8.3	-17.6
JOSH20	Josefov	91	Female	35+	6.4	13.8	39.4	3.3	9.5	-18.2
JOSH21	Josefov	111	Female	35+	18.0	15.5	43.1	3.2	9.0	-17.8
JOSH22	Josefov	113	Female	35+	20.5	15.8	44.0	3.2	9.4	-18.3
JOSH23	Josefov	116	Female	35+	20.0	15.4	42.6	3.2	10.1	-17.4
JOSH24	Josefov	135	Female	35+	18.4	15.4	43.0	3.2	9.8	-18.1
JOSH25	Josefov	144	Female	35+	19.2	15.5	43.2	3.2	8.9	-18.2
JOSH26	Josefov	160	Female	<35	20.8	15.6	42.8	3.2	10.7	-18.0
JOSH27	Josefov	3Z	Female	35+	20.7	15.4	43.3	3.3	9.0	-15.9
JOSH28	Josefov	169	Female	35+	18.8	15.6	43.5	3.2	8.7	-18.0
JOSH29	Josefov	13Z	Female	35+	20.2	15.5	43.2	3.2	10.8	-17.2
JOSH30	Josefov	50	Female	35+	19.8	15.2	42.5	3.2	9.5	-18.1
JOSH31	Josefov	112	Male	35+	19.7	16.1	44.3	3.2	10.4	-17.8
JOSH32	Josefov	23	Male	35+	20.7	14.2	39.4	3.2	10.2	-18.1
JOMH01	Josefov II	98X	Female	35+	20.4	**17.8**	**49.1**	3.2	9.1	-17.6
JOMH02	Josefov II	177X	Male	35+	20.9	16.3	44.9	3.2	9.5	-16.7
JOMH03	Josefov II	183X	Male	35+	17.8	14.5	40.6	3.3	9.7	-17.1
JOMH04	Josefov II	184X	Female	35+	20.6	15.4	43.0	3.2	9.5	-16.8
JOMH05	Josefov II	185X	Female	<35	17.9	14.6	40.5	3.2	8.5	-17.3
JOMH06	Josefov II	186X	Female	35+	18.5	**20.8**	**56.5**	3.1	8.7	-16.9
JOMH07	Josefov II	15bX	Female	35+	20.0	14.8	41.5	3.3	9.8	-17.6
JOMH08	Josefov II	17X	Female	35+	19.6	15.3	42.3	3.2	9.4	-17.4

Sample Code	Site	Grave No.	Sex	Age	Yield (%)	Nitrogen Content (%)	Carbon Content (%)	C:N	$\delta^{15}N_{AIR}$ (‰)	$\delta^{13}C_{PDB}$ (‰)
JOMH09	Josefov II	18X	Male	35+	18.8	11.0	30.8	3.3	9.5	-16.8
JOMH10	Josefov II	20X	Male	35+	20.0	**18.1**	**50.1**	3.2	9.7	-17.0
JOMH11	Josefov II	21X	Male	35+	17.2	14.8	40.9	3.2	9.3	-16.6
JOMH12	Josefov II	22X	Female	35+	18.4	12.6	35.4	3.3	8.8	-17.0
JOMH13	Josefov II	23X	Female	35+	13.5	14.0	38.5	3.2	9.2	-17.4
JOMH14	Josefov II	24X	Male	35+	19.6	15.5	42.8	3.2	10.4	-17.7
JOMH15	Josefov II	28X	Male	35+	2.5	12.1	37.4	3.5	9.5	-17.8
JOMH16	Josefov II	29X	Female	35+	13.4	16.9	47.0	3.3	9.2	-17.9
JOMH17	Josefov II	30X	Female	35+	7.7	13.3	37.6	3.3	9.5	-17.4
JOMH18	Josefov II	32X	Female	<35	16.5	13.6	37.9	3.2	9.6	-15.6
JOMH19	Josefov II	33X	Male	<35	17.4	14.9	43.6	3.4	8.5	-17.0
JOMH20	Josefov II	34X	Male	35+	6.4	13.4	38.1	3.3	9.5	-17.3
JOMH21	Josefov II	37X	Male	35+	17.4	14.5	40.8	3.3	9.3	-16.9
LOUH01	Louky od Břeclavska	1	ND	Adult	16.7	15.2	41.7	3.2	10.6	-17.7
LOUH02	Louky od Břeclavska	2	Male	Adult	18.0	16.1	44.4	3.2	9.1	-17.5
LOUH03	Louky od Břeclavska	3	Female	Adult	17.1	16.6	44.8	3.1	9.5	-17.8
LOUH04	Louky od Břeclavska	5	Male	Adult	19.1	16.0	43.8	3.2	9.5	-17.1
LOUH05	Louky od Břeclavska	6	ND	Adult	7.4	15.2	41.7	3.2	10.7	-17.6
LOUH06	Louky od Břeclavska	8	Male	Adult	18.3	15.9	43.0	3.1	11.1	-17.5
LOUH07	Louky od Břeclavska	9	ND	Adult	12.8	16.8	45.9	3.2	9.1	-17.3
LOUH08	Louky od Břeclavska	10	Male	Adult	14.5	15.6	42.7	3.2	10.0	-17.1
LOUH09	Louky od Břeclavska	11	Male	Adult	18.7	16.3	44.2	3.2	9.5	-16.9
LOUH10	Louky od Břeclavska	7	ND	Adult	18.5	15.8	43.3	3.2	9.7	-17.1

[a]ND – undetermined sex; samples with carbon and nitrogen content higher than recommended maximum in bold font.

TABLE A4. Complete human apatite isotopic data (adults)

Sample Code	Site	Grave No.	Sex	Age	$\delta^{13}C_{coll}$	$\delta^{13}C_{ap}$	$\Delta^{13}C_{coll\text{-}modern}$[a]	$\Delta^{13}C_{ap\text{-}modern}$[a]
MIKH1ap	Mikločice	39	Male	35+	-16.8	-12.2	-20.4	-14.2
MIKH6ap	Mikločice	61	Male	<35	-18.7	-12.0	-20.3	-15.2
MIKH8ap	Mikločice	94	Male	35+	-18.9	-12.7	-20.3	-13.9
MIKH10ap	Mikločice	122	Male	35+	-18.6	-12.3	-20.2	-13.5
MIKH16ap	Mikločice	167	Female	35+	-16.9	-10.6	-20.2	-12.5
MIKH19ap	Mikločice	199	Male	35+	-18.7	-12.5	-20.1	-13.8
MIKH20ap	Mikločice	223	Male	35+	-18.8	-13.7	-18.7	-12.0
MIKH24ap	Mikločice	419	Female	<35	-18.6	-10.9	-18.6	-12.2
MIKH35ap	Mikločice	721	Male	<35	-17.1	-10.7	-18.4	-12.0
MIKH37ap	Mikločice	1197	Female	<35	-17.2	-10.5	-18.3	-13.7
JOSH4ap	Josefov	43	Female	35+	-16.8	-9.6	-21.3	-15.5
JOSH5ap	Josefov	44	Female	35+	-17.3	-11.3	-20.5	-12.5
JOSH8ap	Josefov	73	Female	35+	-17.1	-10.8	-20.3	-13.9
JOSH9ap	Josefov	76	Female	35+	-18.6	-12.7	-20.1	-14.2
JOSH11ap	Josefov	79	Female	35+	-18.8	-12.5	-18.8	-12.8
JOSH12ap	Josefov	80	Female	35+	-17.3	-11.8	-18.8	-13.3
JOSH13ap	Josefov	85	Male	35+	-19.8	-14.0	-18.7	-12.7
JOSH14ap	Josefov	109	Male	35+	-19.0	-11.0	-18.6	-12.3
JOSH27ap	Josefov	3Z	Female	35+	-15.9	-9.4	-18.3	-11.1
JOSH29ap	Josefov	13Z	Female	35+	-17.2	-11.2	-17.4	-10.9
LOUH01ap	Louky od Břeclavska	1	ND	Adult	-17.7	-11.8	-19.2	-13.3
LOUH02ap	Louky od Břeclavska	2	Male	Adult	-17.5	-11.9	-19.0	-13.4
LOUH03ap	Louky od Břeclavska	3	Female	Adult	-17.8	-11.7	-19.3	-13.2

Sample Code	Site	Grave No.	Sex	Age	$\delta^{13}C_{coll}$	$\delta^{13}C_{ap}$	$\Delta^{13}C_{coll\text{-}modern}$	$\Delta^{13}C_{ap\text{-}modern}$
LOUH04ap	Louky od Břeclavska	5	Male	Adult	-17.1	-10.8	-18.6	-12.3
LOUH05ap	Louky od Břeclavska	6	ND	Adult	-17.6	-12.1	-19.1	-13.6
LOUH06ap	Louky od Břeclavska	8	Male	Adult	-17.5	-11.3	-19.0	-12.8
LOUH07ap	Louky od Břeclavska	9	ND	Adult	-17.3	-11.5	-18.8	-13.0
LOUH08ap	Louky od Břeclavska	10	Male	Adult	-17.1	-11.2	-18.6	-12.7
LOUH09ap	Louky od Břeclavska	11	Male	Adult	-16.9	-11.1	-18.5	-12.6
LOUH10ap	Louky od Břeclavska	7	ND	Adult	-17.1	-10.6	-18.6	-12.1

[a] after a correction of 1.5‰ is subtracted from archaeological values for comparison because of the Suess Effect.

TABLE A5. Complete human isotopic data (subadults)

Sample code[a]	Dental age	Sampled tooth[b]	Tooth						Bone						Tooth *vs.* bone isotopic difference		Feeding status[d]
			Yield	%C	%N	C:N	$\delta^{13}C$	$\delta^{15}N$	Yield	%C	%N	C:N	$\delta^{13}C$	$\delta^{15}N$	$\Delta^{13}C^{c}$	$\Delta^{15}N^{c}$	
MIKS1	0.4-0.8	dm1	16.4	39.8	14.4	3.2	-18.4	14.8	15.9	38.3	13.6	3.3	-18.2	14.0	-0.2	0.8	breastfed
MIKS2	0.9-1.3	dc	11.2	41.3	15.1	3.2	-14.2	15.0	13.5	40.0	14.2	3.3	-15.4	13.7	1.1	1.4	breastfed
MIKS3	0.7-1.1	di1, di2	20.5	36.6	13.3	3.2	-14.5	17.9	17.2	39.1	14.2	3.2	-15.6	16.6	1.1	1.3	breastfed
MIKS4	1.3-1.7	dm1	19.5	38.9	14.1	3.2	-18.2	12.3	14.0	39.7	14.3	3.2	-17.9	13.2	-0.3	-0.9	weaned
MIKS5	1.3-1.7	di2 (2x)	22.1	33.3	12.0	3.2	-17.9	13.0	13.9	36.7	13.2	3.2	-18.2	12.4	0.3	0.7	breastfed
MIKS6	1.8-2.2	dm1	9.7	36.7	13.2	3.2	-17.5	13.1	17.0	39.0	14.0	3.2	-17.6	12.9	0.2	0.2	ND
MIKS7	1.7-2.1	dm1	23.0	35.1	12.7	3.2	-16.7	14.7	15.6	39.3	14.3	3.2	-16.6	14.5	-0.1	0.2	ND
MIKS8	1.1-1.5	dm1	11.2	35.4	12.7	3.2	-16.8	19.2	13.3	40.4	14.5	3.2	-17.2	18.6	0.4	0.6	breastfed
MIKS9	1.9-2.3	dm2	21.8	36.3	12.9	3.3	-17.7	12.1	16.1	37.1	13.2	3.3	-17.4	12.9	-0.3	-0.7	weaned
MIKS10	2.4-2.8	dc (2x)	12.4	34.2	12.2	3.3	-16.8	11.5	14.7	38.1	13.5	3.3	-17.8	10.7	1.0	0.9	breastfed
MIKS11	2.6-3.0	dm2	12.7	39.4	13.9	3.3	-15.4	11.9	17.6	38.4	13.4	3.3	-15.3	11.3	-0.1	0.6	breastfed
MIKS12	2.3-2.7	dm2	19.8	38.0	13.6	3.2	-16.9	12.6	17.9	39.0	13.8	3.3	-17.5	12.4	0.6	0.2	ND
MIKS13	2.5-2.9	dc (2x)	4.5	33.5	12.0	3.2	-16.9	12.2	5.6	38.5	14.0	3.2	-17.2	12.3	0.3	-0.2	ND
MIKS14	3.5-3.9	dm2	4.8	30.8	10.8	3.3	-17.6	11.5	8.7	37.4	13.4	3.2	-17.9	11.8	0.3	-0.3	ND
MIKS15	2.2-2.6	dm2	21.7	42.2	15.2	3.2	-17.3	12.6	18.4	40.1	14.4	3.2	-17.5	11.7	0.2	0.9	breastfed
MIKS16	2.8-3.2	dm2	22.4	38.1	13.3	3.3	-17.5	11.7	18.2	35.6	12.7	3.2	-17.3	11.7	-0.2	0.0	ND
MIKS17	3.0-3.4	dm2	4.3	30.8	11.0	3.2	-18.3	12.7	11.8	38.4	13.8	3.2	-18.8	12.7	0.5	-0.1	ND
MIKS18	3.8-4.2	dm2	20.9	35.1	12.6	3.2	-17.6	12.4	18.6	34.4	12.3	3.2	-17.9	11.8	0.3	0.5	breastfed
MIKS19	4.3-5.5	dm2	20.0	32.9	11.8	3.2	-17.9	11.4	17.6	34.4	12.3	3.3	-17.1	12.1	-0.9	-0.8	weaned
MIKS20	3.3-3.7	dm2	5.3	32.3	11.5	3.2	-14.9	11.3	16.2	37.9	13.5	3.2	-16.2	10.9	1.2	0.3	ND

Sample code[a]	Dental age	Sampled tooth[b]	Tooth						Bone						Tooth *vs.* bone isotopic difference		Feeding status[d]
			Yield	**%C**	**%N**	**C:N**	**$\delta^{13}C$**	**$\delta^{15}N$**	**Yield**	**%C**	**%N**	**C:N**	**$\delta^{13}C$**	**$\delta^{15}N$**	**$\Delta^{13}C$[c]**	**$\Delta^{15}N$[c]**	
MIKS21	4.1-4.5	dm2	21.5	35.9	12.9	3.2	-18.5	12.0	12.6	33.4	12.0	3.2	-18.7	11.6	0.3	0.5	breastfed
MIKS22	3.0-3.4	dm2	19.6	35.0	12.7	3.2	-17.5	11.6	19.8	39.9	14.4	3.2	-17.7	10.9	0.1	0.7	breastfed
MIKS23	5.0-5.4	dm2	20.8	38.7	14.0	3.2	-18.8	11.2	18.5	39.6	14.2	3.2	-18.7	10.9	-0.1	0.2	ND
JOSS2	1.1-1.5	di1, di2	22.9	37.3	13.3	3.3	-14.7	13.4	17.8	37.2	13.5	3.2	-14.9	11.8	0.2	1.6	breastfed
JOSS3	0.8-1.2	di1, di2	21.7	40.6	14.3	3.3	-16.8	13.5	20.2	42.2	15.0	3.3	-17.0	12.5	0.2	1.0	breastfed
JOSS4	1.2-1.6	dm1	3.6	35.4	11.7	3.5	-16.8	11.4	5.9	40.4	13.6	3.5	-17.1	11.1	0.3	0.3	ND
JOSS5	1.1-1.5	di2 (2x)	18.2	40.7	14.8	3.2	-15.7	14.1	13.3	37.8	13.2	3.3	-16.3	12.7	0.6	1.4	breastfed
JOSS6	1.6-2.0	dm1	14.2	37.9	13.2	3.3	-16.4	15.0	10.5	39.0	13.6	3.3	-16.3	13.5	-0.1	1.5	breastfed
JOSS7	1.9-2.3	dm1	21.4	33.5	11.9	3.3	-17.0	13.0	11.9	39.3	13.7	3.3	-17.8	12.5	0.8	0.5	breastfed
JOSS8	2.4-2.8	dc	18.1	41.1	14.8	3.2	-16.3	12.6	17.3	34.9	12.4	3.3	-16.3	12.8	0.0	-0.2	ND
JOSS9	1.8-2.2	dm1	19.4	39.1	14.1	3.2	-17.3	11.1	17.9	42.5	15.0	3.3	-17.8	10.5	0.5	0.5	breastfed
JOSS10	2.3-3.7	dm2	21.6	36.3	13.1	3.2	-16.0	11.6	22.5	36.4	13.2	3.2	-16.2	11.0	0.2	0.7	breastfed
JOSS11	2.0-2.4	dm1	18.5	39.1	14.1	3.2	-16.6	12.6	17.4	39.8	14.3	3.2	-17.0	11.7	0.4	0.9	breastfed
JOSS12	2.6-3.0	dm2	19.8	38.6	13.9	3.2	-16.8	12.9	15.2	39.9	14.3	3.2	-17.1	12.9	0.3	0.0	ND
JOSS13	1.7-2.1	dm2	13.9	42.6	15.4	3.2	-17.1	12.4	16.5	39.0	13.9	3.3	-16.7	12.5	-0.4	-0.1	ND
JOSS14	2.5-2.9	dm2	17.7	39.8	14.3	3.2	-18.0	12.2	17.7	37.7	13.5	3.2	-18.7	11.3	0.7	0.9	breastfed
JOSS15	2.5-2.9	dm2	23.3	35.0	12.4	3.3	-17.4	13.2	17.5	34.3	12.0	3.3	-16.2	14.0	-1.2	-0.8	weaned
JOSS16	2.7-3.1	dm2	7.6	32.2	11.5	3.3	-17.7	10.1	17.7	41.3	14.8	3.2	-17.6	10.8	-0.1	-0.7	weaned
JOSS17	3.1-3.5	dm2	12.1	39.5	14.1	3.2	-17.3	11.2	18.8	41.3	14.7	3.3	-17.5	10.9	0.2	0.3	ND
JOSS18	3.4-3.8	dm2	18.8	41.2	14.7	3.2	-18.1	10.6	10.0	40.8	14.4	3.3	-18.5	10.5	0.4	0.1	ND
JOSS20	4.8-5.6	M1	18.7	40.8	14.8	3.2	-18.1	10.5	19.9	42.1	15.1	3.2	-18.1	9.9	0.0	0.6	?

[a] MIK = Mikulčice; JOS = Josefov.

[b] di1, di2 = first, second deciduous incisor; dc = deciduous canine; dm1, dm2 = first, second deciduous molar; M1 = first permanent molar.

[c] Relative difference between tooth and bone; significant (>±0.2) differences in bold font.

[d] Based on $\delta^{15}N$(t-b); ND = no significant isotopic difference.